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# Insights into the evolution of the Thomson Orogen from geochronology, geochemistry, and zircon isotopic studies of magmatic rocks

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## ABSTRACT

Zircon U–Pb ages,  $\epsilon\text{Hf}(t)$ , and  $\delta^{18}\text{O}$  isotopic data together with geochemistry and limited Sm–Nd results from magmatic rocks sampled in deep-basement drill cores from undercover parts of the Thomson Orogen provide strong temporal links with outcropping regions of the orogen and important clues to its evolution and relationship with the Lachlan Orogen. SHRIMP U–Pb zircon ages show that magmatism of Early Ordovician age is widespread across the central, undercover regions of the Thomson Orogen and occurred in a narrow time-window between 480 and 470 Ma. These rocks have evolved  $\epsilon\text{Hf}(t)_{\text{Zrn}}$  (–12.18 to –6.26) and  $\epsilon\text{Nd}$  (–11.3 to –7.1), and supracrustal  $\delta^{18}\text{O}_{\text{Zrn}}$  (7.01–8.50‰), which is in stark contrast to Early Ordovician magmatic rocks in the Lachlan Orogen that are isotopically juvenile. Two samples have late Silurian ages (425–420 Ma), and four have Devonian ages (408–382 Ma). The late Silurian rocks have evolved  $\epsilon\text{Hf}(t)_{\text{Zrn}}$  (–6.42 to –4.62) and supracrustal  $\delta^{18}\text{O}_{\text{Zrn}}$  (9.26–10.29‰) values, while the younger Devonian rocks show a shift toward more juvenile  $\epsilon\text{Hf}(t)_{\text{Zrn}}$ , a trend that is also seen in rocks of this age in the Lachlan Orogen. Interestingly, two early Late Devonian samples have juvenile  $\epsilon\text{Hf}(t)_{\text{Zrn}}$  (0.01–1.92) but supracrustal  $\delta^{18}\text{O}_{\text{Zrn}}$  (7.45–8.77‰) indicating rapid recycling of juvenile material. Two distinct Hf–O isotopic mixing trends are observed for magmatic rocks of the Thomson Orogen. One trend appears to have incorporated a more evolved supracrustal component and is defined by samples from the northern two-thirds of the Thomson Orogen, while the other trend is generally less evolved and from samples in the southern third of the Thomson Orogen and matches the isotopic character of rocks from the Lachlan Orogen. The spatial association of the Early Ordovician magmatism with the more evolved metasedimentary signature suggests that at least the northern part of the Thomson Orogen is underlain by older pre-Delamerian metasedimentary rocks.

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Eastern Australia; Thomson Orogen; magmatic rocks; drill core; zircon; geochronology; geochemistry; zircon Hf and O isotopes

## Introduction

The Thomson Orogen of eastern Australia (as defined by Fergusson, Henderson, Hutton, & Withnall, 2013; Glen *et al.*, 2013) covers ~1,000,000 km<sup>2</sup> but is poorly understood and underexplored due to extensive sedimentary cover that in places reaches thicknesses of 4 km. This has necessitated a reliance on geophysical datasets to advance our understanding of this region and its relationships within the broader Tasmanides of eastern Australia (Burton, 2010; Glen *et al.*, 2010, 2013; Korsch *et al.*, 2012; Roach, 2015). Outcropping rocks occur at the margins of the orogen in northern Queensland (Fergusson, Carr, Fanning, & Green, 2001; Fergusson, Henderson, Fanning, & Withnall, 2007a; Henderson, Innes, Fergusson, Crawford, & Withnall, 2011), northwestern New South Wales (Greenfield, Musgrave, Bruce, Gilmore, & Mills, 2011), and as scattered exposures

associated with the Eulo Ridge in south-central Queensland (Bultitude & Cross, 2013; Purdy *et al.*, 2016a). Structural, chemical, and geochronological investigations of rocks in these areas and the lack of sample material from the undercover regions have necessarily meant that interpretations from the outcropping regions have been extrapolated to the entire orogen.

A key to a better understanding of the Thomson Orogen is to sample the concealed basement rocks. Throughout the Thomson Orogen, ~160 petroleum, stratigraphic, and mineral exploration drill holes have penetrated the cover and retrieved samples of metasedimentary and igneous basement rocks. Most of these basement intersections have been described in detail (Murray, 1994; Brown, Carr, & Purdy, 2012), but until recently, have not been analysed with modern geochronological and isotopic techniques.

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Recent work has focused on the metasedimentary units where detrital zircon age spectra and maximum depositional ages from SHRIMP U–Pb dating have helped to characterise Thomson Orogen stratigraphy and provenance (Cross *et al.*, 2015; Cross, Purdy, Bultitude, Brown, & Carr, 2016; Fraser *et al.*, 2014; Kositsin, Purdy, Brown, Bultitude, & Carr, 2015a; Kositsin *et al.*, 2015b; Purdy, Cross, Brown, Carr, & Armstrong, 2016b). However, crucial to understanding the development of the Thomson Orogen is knowledge of the nature, timing, and origin of magmatic events. Igneous rocks have the additional benefit of providing a geochemical and/or isotopic glimpse of mid to lower crustal source rocks and can therefore provide a better understanding of the tectonic development of the Thomson Orogen and Tasmanides.

Available geochronology for igneous rocks in basement cores is limited to nine samples reported in abstract format (Draper, 2006). The SHRIMP U–Pb zircon ages for these samples range from middle Cambrian to Late Devonian. Although published without thorough peer review, the interpreted ages of these samples have propagated into ~20 research papers. The extent to which these ages have been cited is testament to how important they are to any consideration of the Tasmanides.

In this contribution, we fully report the SHRIMP U–Pb geochronology of the nine samples mentioned by Draper (2006) and supplement this work with (1) new SHRIMP U–Pb geochronology from other basement cores and remote outcrops, (2) new zircon Hf–O isotopic data, and (3) whole-rock geochemistry and Nd isotopic data. These data provide clues to the development of the Thomson Orogen, as well as reveal fundamental differences and similarities with the Lachlan Orogen.

## Background geology

The Thomson Orogen formed along part of the Pacific margin of Gondwana from the Neoproterozoic to the Paleozoic. It is a major component of the Tasmanides (Figure 1) that records the growth of eastern Australia following break-up of the Rodinia supercontinent. The Delamerian, Lachlan, Thomson, Mossman, and New England orogens, which comprise the Tasmanides, are divided on the basis of geophysical patterns, structure, and age of component units. To the south, rocks deformed during the Delamerian Orogeny (514–490 Ma; Foden,

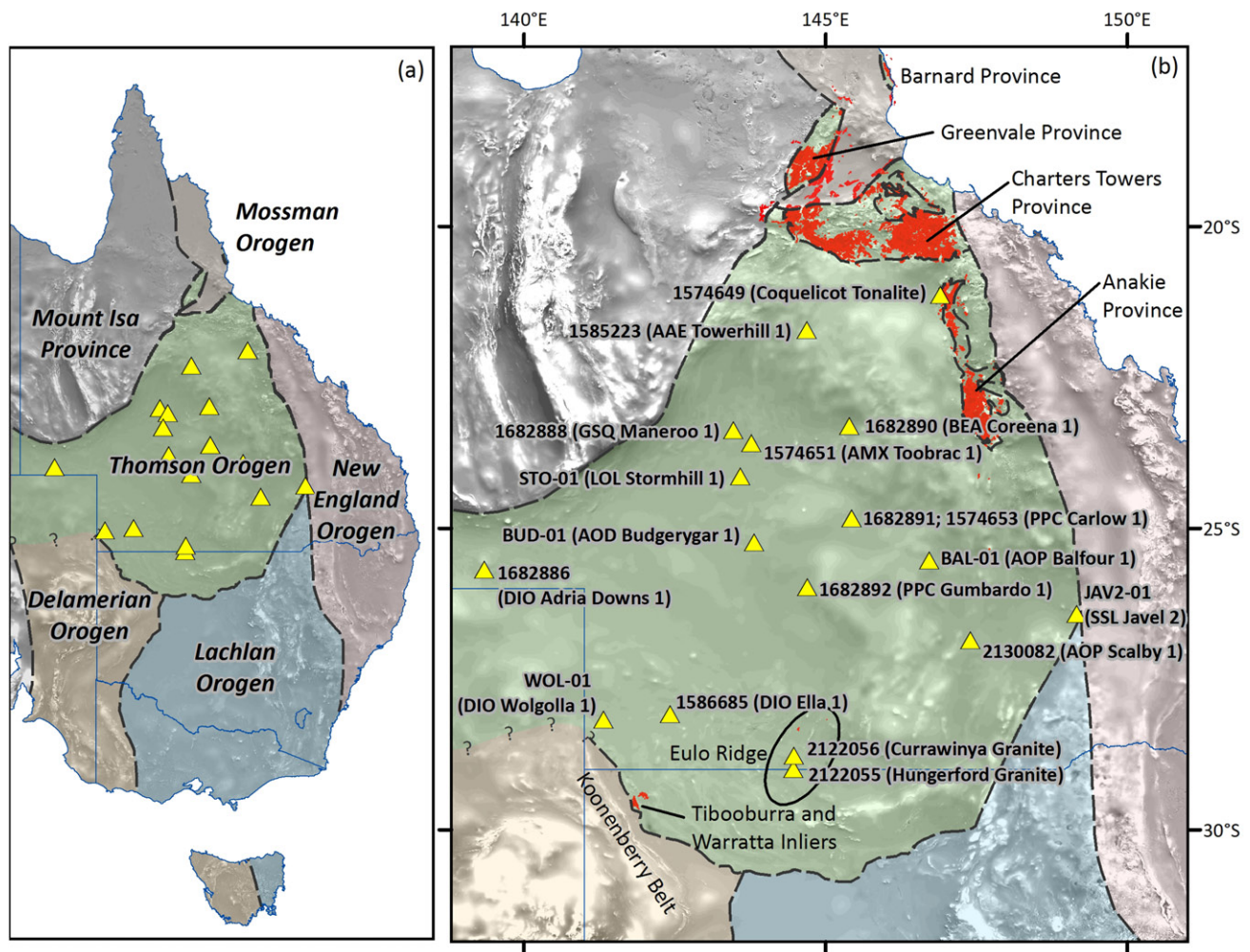


Figure 1. Distribution of Tasmanides showing location of key provinces and drill holes in the Thomson Orogen. Red polygons are areas of outcrop.

Elburg, Dougherty-Page, & Burt, 2006) are divided as a separate component (Delamerian Orogen) from the younger Lachlan Orogen (Champion, 2016, figure 3.10). To the north, this division has not been achieved and it is likely that the Thomson Orogen includes rocks emplaced both before and after the Delamerian Orogeny.

The majority of the Thomson Orogen is concealed below thick sedimentary cover. SHRIMP U–Pb zircon geochronology for metasedimentary rocks sampled from deep drill cores demonstrates strong similarities between the undercover part of the Thomson Orogen and outcropping regions and confirms the presence of at least two stratigraphic packages (Purdy *et al.*, 2016b). The oldest metasedimentary succession is inferred to have been deposited during the late Neoproterozoic to early Cambrian. Outcropping examples occur in the Charters Towers Province (Fergusson *et al.*, 2007a) and Anakie Province (Fergusson *et al.*, 2001), while undercover probable correlatives have been grouped into the Machattie beds by Carr, Purdy, and Brown (2014) and occur near the western margin of the Thomson Orogen (Purdy *et al.*, 2016b; Figure 2). Overlying these rocks is a widespread package of dominantly low-grade, quartz-rich turbiditic metasedimentary rocks deposited from the middle–late Cambrian to Early Ordovician. Outcropping units occur in the Charters Towers and Anakie provinces (Fergusson *et al.*, 2001, 2007a) as well as in the undercover parts of the Thomson Orogen, where they are represented by the Thomson beds (Carr *et al.*, 2014; Purdy *et al.*, 2016b; Figure 2).

The magmatic history of the Thomson Orogen extends from the late Neoproterozoic through to the Triassic and several distinct pulses of activity are recognised. The earliest preserved magmatism is represented by mafic schists in the Bathampton Metamorphics (Anakie Metamorphic Group). These are interpreted as late Neoproterozoic in age and associated with a rifting event (Fergusson, Offler, & Green, 2009). As such, they may correlate with the Mount Arrowsmith Volcanics in the Koonenberry Belt of western New South Wales (Delamerian Orogen) (Crawford, Stevens, & Fanning, 1997; Greenfield *et al.*, 2011).

Cambrian magmatism is recorded adjacent to the Thomson Orogen in the Koonenberry Belt of western New South Wales (Mount Wright Arc) and Stavely region of western Victoria (Stavely Arc). This magmatism occurred prior to or during the Delamerian Orogeny and has been attributed to a continental volcanic arc formed along the eastern margin of Gondwana (Cayley, 2011; Greenfield *et al.*, 2011). Volcanic rocks of similar age occur in the sub-surface Warburton Basin at the western extremity of the Thomson Orogen (Mooracoochie Volcanics). This has led some workers to support a continuation of the Mount Wright Arc into the Warburton Basin area as the Gidealba Arc (Gatehouse, 1986; Scheibner & Veevers, 2000); however, the tectonic affinity of volcanic rocks in the Warburton Basin is contested (Purdy, Carr, & Brown, 2013). The

relationship between the Warburton Basin and the Thomson Orogen is also unclear although it is likely that they are equivalent (Purdy *et al.*, 2016b).

Following the Delamerian Orogeny, voluminous magmatism in the Thomson Orogen occurred during the extensional Larapinta Event in the late Cambrian and Early to Middle Ordovician (490–460 Ma; Fergusson *et al.*, 2007b). Extensive volcanic and intrusive magmatism is recorded in the Charters Towers Province by the dominantly silicic Seventy Mile Range Group, older components of the Ravenswood Batholith and the Fat Hen Creek Complex (Fergusson *et al.*, 2007a). In the Greenvale Province, it is recorded by the Balcooma Metavolcanic Group and the Lynwater Complex, while in the Anakie Province, it is represented by the Mooramin Granite and Coquelicot Tonalite. Igneous rocks of similar age also occur in the central undercover Thomson Orogen and comprise the informally named, Maneroo volcanics of Carr *et al.* (2014) and felsic intrusions intersected in AOD Budgerygar 1, LOL Stormhill 1, and AMX Toobrac 1 (Figure 2).

The next major phase of magmatism occurred in the mid Silurian to Devonian (430–395 Ma). In the Charters Towers Province, intrusions of this age are grouped into the Pama Igneous Association and represent the major component of the Ravenswood Batholith (Hutton, Rienks, Tenison-Woods, Hartley, & Crouch, 1994). In the southern part of the Thomson Orogen, late Silurian intrusions are also abundant and include the Tibooburra Suite, Hungerford Granite, and granites intersected in drill holes DIO Ella 1, TEA Roseneath 1, and DIO Wolgolla 1, which form a distinctive batholithic-scale belt of intrusions (Ella belt of Purdy, Hegarty, & Doublier, 2018). Another distinctive pulse of volcanism occurred from 408 to 403 Ma associated with a widespread extensional event resulting in opening of the Adavale Basin and other Devonian basins throughout the Thomson Orogen. This magmatism is recorded by volcanic deposits that comprise the Gumbardo Formation and is dated in drill holes PPC Carlow 1 and PPC Gumbardo 1.

The Middle Devonian (395–380 Ma) saw another period of magmatism in the Thomson Orogen that is recorded by the Retreat Batholith and Theresa Creek Volcanics in the Anakie Province, the Eulo Granite and Currawinya Granite in the southern Thomson Orogen, and crystal-rich ignimbrite in the central Thomson Orogen intersected in drill holes APC Thunderbolt 1 and AAE Towerhill 1. In the Late Devonian (380–360 Ma), voluminous S-type granites that form the Roma granites (Murray, 1994) were emplaced in the Roma Shelf region immediately east of the southern Thomson Orogen.

Granite as young as  $235 \pm 1.4$  Ma (Burton, Trigg, & Black, 2007) and a suite of Permian to Triassic plugs, stocks, and dykes (Dwyer, Collins, Hack, Hegarty, & Huang, 2018) have recently been identified in the southern Thomson Orogen but these are individually small volume features.



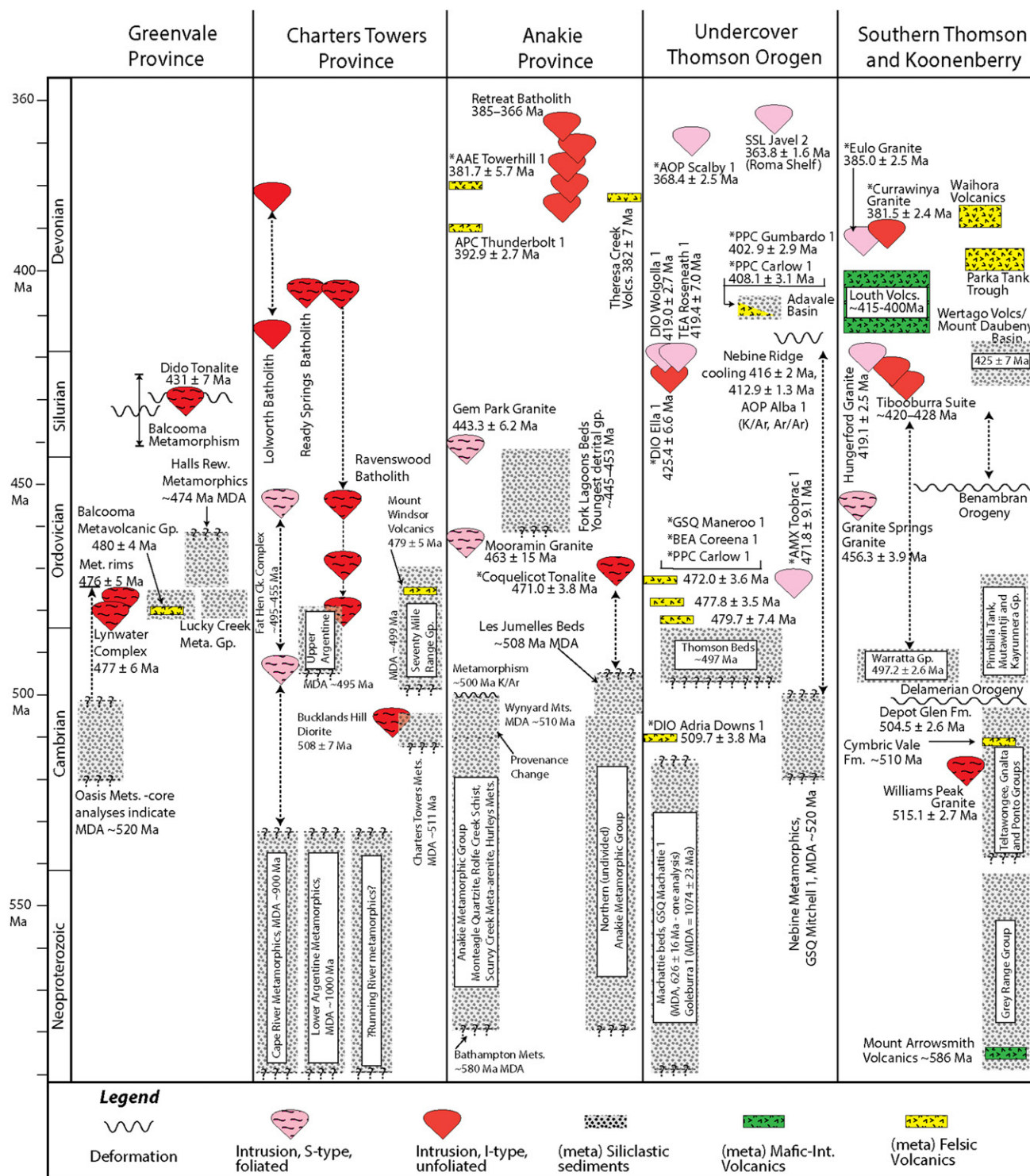


Figure 2. Time-space plot for the Thomson Orogen showing major metasedimentary and volcanic rocks and intrusions. Names marked with an asterisk (\*) are units for which isotopic data are presented in this study. Adapted from Purdy *et al.* (2016b).

## Methods

Igneous rocks used in this study include 10 samples from petroleum and stratigraphic drill holes and three samples from surface outcrop (Table 1). SHRIMP U-Pb zircon analyses were carried out on the SHRIMP II ion microprobe at the Australian National University, Canberra, SHRIMP B at

the Curtin University of Technology, Perth, Western Australia, and SHRIMP IIe at Geoscience Australia, Canberra. Zircon O and Hf isotopic analyses were completed for 12 of the samples. Oxygen isotopes were measured on SHRIMP II at the Australian National University (ANU) and the  $\delta^{18}\text{O}$  values are reported relative to VSMOW (Vienna Standard Mean Ocean Water; Baertschi, 1976). The Lu and

**Table 1.** Location information for samples analysed as a part of this study.

GA sample no (well name/sample name)	Unit	Lithology	Longitude	Latitude	Interval/depth (m)
1682886 (DIO Adria Downs 1)	Mooracoochie Volcanics	Rhyolitic ignimbrite	139.343736	-25.693506	1527.05–1530.1
1682888 (GSQ Maneroo 1)	Maneroo volcanics	Porphyritic rhyolite	143.466666	-23.383333	1168.79–1168.97
1682890 (BEA Coreena 1)	Maneroo volcanics	Porphyritic dacite	145.389728	-23.313181	1586–1586.08
1574653 (PPC Carlow 1)	Maneroo volcanics	Felsic autoclastic volcanic	145.431147	-24.839292	3660–3660.05
1574651 (AMX Toobrac 1)	Unnamed granite	bt–ms monzogranite	143.765603	-23.590975	1106.4–1106.7
1574649 (Coquelicot Tonalite)	Coquelicot Tonalite	bt–hbl tonalite	146.899348	-21.137495	outcrop sample
1586685 (DIO Ella 1)	Ella Granite	bt–ms monzogranite	142.422617	-28.087656	1278–1278.1
2122055 (Hungerford Granite)	Hungerford Granite	ms–bt monzogranite	144.461530	-28.995782	outcrop sample
1682891 (PPC Carlow 1)	Gumbardo Formation	Rhyolitic ignimbrite	145.431147	-24.839292	3292–3292.1
1682892 (PPC Gumbardo 1)	Gumbardo Formation	Rhyolitic ignimbrite	144.695889	-25.979575	3700.07–3700.18
1585223 (AAE Towerhill 1)	Unnamed volcanic	Rhyolitic ignimbrite	144.681683	-21.716800	1487–1487.2
2122056 (Currawinya Granite)	Currawinya Granite	bt monzogranite	144.468680	-28.780044	Outcrop sample
2130082 (AOP Scalby 1)	Scalby Granite	bt–ms granite	147.396977	-26.863438	858.9–860.1

bt: biotite; hbl: hornblende; ms: muscovite.

Hf isotopes were measured on the ANU ThermoFinnigan multi-collector LA-ICP-MS. Abundances of major and trace elements in whole samples were determined at Geoscience Australia, Canberra. Major and minor elements were determined by wavelength-dispersive X-ray fluorescence and selected trace elements and Rare Earth elements were analysed by Inductively Coupled Plasma Mass Spectrometry (ICPMS). Sm–Nd isotope analyses were carried out at the University of Melbourne using a NU Plasma multi-collector ICP-MS.

Full location and sample information, zircon images, analytical procedures, SHRIMP session information, and data for each method are compiled in the [Supplementary papers](#).

## Results

Discussed below are the results of zircon U–Pb, O, and Hf isotopic studies of 13 igneous samples from the Thomson Orogen (seven volcanic and six intrusive rocks). Zircons considered to have formed from mantle-like sources have  $\delta^{18}\text{O}$  values within error of the normal mantle zircon range  $5.3 \pm 0.6\text{‰}$  ( $2\sigma$ ) (Valley *et al.*, 2005), and positive  $\varepsilon\text{Hf}(t)$  values. External uncertainties for oxygen isotope values reported have an upper limit of  $0.50\text{‰}$ . We therefore classify zircons with  $\delta^{18}\text{O}$  values between 4.2 and  $6.4\text{‰}$  as normal mantle-like zircon. Also discussed are results of whole-rock geochemistry and Sm–Nd isotopic studies. Table 1 shows the details of the samples and Table 2 is the summary of the zircon, U–Pb,  $\delta^{18}\text{O}$ , and initial  $\varepsilon\text{Hf}(t)$  and whole-rock  $\varepsilon\text{Nd}$  values for each of the samples. Geochemistry data are included in the [Supplementary papers, Table S14](#).

The U–Pb zircon isotopic results reported here for three samples are a synthesis of full and detailed results reported in Cross *et al.* (2015; 2122055 [Hungerford Granite]; 2122056 [Currawinya Granite]) and Kositcin *et al.* (2015a; 2130082 [AOP Scalby 1]). All other samples were analysed between 2004 and 2005; the ages for nine of these were mentioned in an abstract by Draper (2006), while the results for sample 1574649 (Coquelicot Tonalite) have not previously been reported. SHRIMP U–Pb data are also

available from Geoscience Australia's Geochronology Delivery database (<http://www.ga.gov.au/geochron-sapub-web/>).

### 1682886 (DIO Adria Downs 1)

Sample 1682886 (DIO Adria Downs 1) is an altered, fine-grained, welded rhyolitic ignimbrite with geochemical characteristics (elevated Y, HREE, Zn, Zr, Ga/Al<sub>2</sub>O<sub>3</sub>) that suggest A-type affinities. Zircons recovered comprise a homogeneous population of mostly broken fragments with average diameters of about 30  $\mu\text{m}$ . Intact grains are euhedral with sharp terminations and have aspect ratios that range from 1 to 6. Cathodoluminescence (CL) images show simple oscillatory zoning. Sixty-one analyses were conducted on 61 zircons from this sample (Figure 3a; [Supplementary papers, Table S1.1](#)). Seven grains have common  $^{206}\text{Pb}$  proportions  $>1\text{ wt}\%$  and were removed from interpretations. The remaining analyses have moderate uranium concentrations (median 314 ppm) and Th/U (median 0.77). Two grains are older than the main population and represent inheritance at ca 555 Ma. The remaining 52 analyses have the same age within their analytical uncertainties and yield a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $509.7 \pm 3.8\text{ Ma}$  (MSWD = 1.37, POF = 0.04), which is interpreted as the eruptive age for this rock. Twenty-two oxygen and 20 hafnium isotopic analyses were undertaken (Figure 4; [Supplementary papers, Tables S1.2 and S1.3](#)). The  $\delta^{18}\text{O}_{\text{Zrn}}$  from 22 analyses ranges from 7.08 to  $8.20\text{‰}$  and is dispersed beyond uncertainty (MSWD = 4.3, POF  $\leq 0.025$ ). The robust median for this grouping (which ignores the individual uncertainties) is  $7.49 + 0.22/-0.15\text{‰}$ . Initial  $\varepsilon\text{Hf}(t)_{\text{Zrn}}$  from 20 analyses range between  $-6.8$  and  $-0.5$  but is significantly scattered (MSWD = 2.84, POF  $\leq 0.025$ ). Removing the two lowest values removes the scatter (MSWD = 1.32, POF = 0.17) and gives a weighted mean  $\varepsilon\text{Hf}(t)_{\text{Zrn}}$  value of  $-2.82 \pm 0.52$ . The sample has a whole-rock  $\varepsilon\text{Nd}(t)$  of  $-7.2$ .

### 1682888 (GSQ Maneroo 1) – Maneroo volcanics

Sample 1682888 (GSQ Maneroo 1) is an altered porphyritic rhyolite. Similar to the Adria Downs sample, the

**Table 2.** U–Pb, O, and Hf isotope data summary. Whole-rock Nd isotope data also shown where analysed.

GA sample no. (well name/sample name)	Age (Ma) (95% confidence)	$\epsilon\text{Hf}(t)$ and $\epsilon\text{Nd}$ (95% confidence)	$\delta^{18}\text{O}_{\text{‰}}$ (95% confidence)
1682886 (DIO Adria Downs 1)	509.7 $\pm$ 3.8	–2.82 $\pm$ 0.52 ( $n$ = 18) $\epsilon\text{Nd}$ = –7.2	7.49 $\pm$ 0.22/–0.15 ( $n$ = 22) <sup>a</sup>
1682888 (GSQ Maneroo 1)	472.0 $\pm$ 3.6	–10.46 $\pm$ 0.48 ( $n$ = 17) $\epsilon\text{Nd}$ = –10.0	8.10 $\pm$ 0.18/–0.14 ( $n$ = 20) <sup>a</sup>
1682890 (BEA Coreena 1)	477.8 $\pm$ 3.5	–6.26 $\pm$ 0.29 ( $n$ = 22) $\epsilon\text{Nd}$ = –7.1	7.01 $\pm$ 0.12/–0.23 ( $n$ = 22) <sup>a</sup>
1574653 (PPC Carlow 1)	479.7 $\pm$ 7.4	–12.18 $\pm$ 0.50 ( $n$ = 15) $\epsilon\text{Nd}$ = –11.3	8.50 $\pm$ 0.14/–0.33 ( $n$ = 20) <sup>a</sup>
1574651 (AMX Toobrac 1)	471.8 $\pm$ 9.1	–10.63 $\pm$ 2.72 ( $n$ = 4) $\epsilon\text{Nd}$ = –9.1	8.30 $\pm$ 1.47/–0.44 ( $n$ = 5) <sup>a</sup>
1574649 (Coquelicot Tonalite)	471.0 $\pm$ 3.8	–	–
1586685 (DIO Ella 1)	425.4 $\pm$ 6.6	–6.42 $\pm$ 0.72 ( $n$ = 14)	10.29 $\pm$ 0.09/–0.52 ( $n$ = 15) <sup>a</sup>
2122055 (Hungerford Granite)	419.1 $\pm$ 2.5	–4.62 $\pm$ 1.2/–0.80 ( $n$ = 19) <sup>a</sup>	9.26 $\pm$ 0.11/–0.23 ( $n$ = 22) <sup>a</sup>
1682891 (PPC Carlow 1)	408.1 $\pm$ 3.1	–1.73 $\pm$ 0.82 ( $n$ = 12)	6.30 $\pm$ 0.24/–0.26 ( $n$ = 14) <sup>a</sup>
1682892 (PPC Gumbardo 1)	402.9 $\pm$ 2.9	0.51 $\pm$ 0.32 ( $n$ = 19)	6.01 $\pm$ 0.15 ( $n$ = 18)
1585223 (AAE Towerhill 1)	381.7 $\pm$ 5.7	–1.72 $\pm$ 0.36 ( $n$ = 19) $\epsilon\text{Nd}$ = –3.5	5.78 $\pm$ 0.20/–0.14 ( $n$ = 20) <sup>a</sup>
2122056 (Currawinya Granite)	381.5 $\pm$ 2.5	1.92 $\pm$ 1.3/–0.97 ( $n$ = 17) <sup>a</sup> $\epsilon\text{Nd}$ = –3.42	7.45 $\pm$ 0.36/–0.40 ( $n$ = 20) <sup>a</sup>
2130082 (AOP Scalby 1)	368.4 $\pm$ 2.5	0.01 $\pm$ 0.46/–2.0 ( $n$ = 17) <sup>a</sup>	8.77 $\pm$ 0.12/–0.30 ( $n$ = 19) <sup>a</sup>

<sup>a</sup>Robust median value and uncertainty. All other ages,  $\epsilon\text{Hf}(t)$  and  $\delta^{18}\text{O}$  values are weighted means.

sample is significantly altered (lost CaO and Na<sub>2</sub>O) and is difficult to classify; however, the unit is most likely an I-type. The zircons from this rock are a homogeneous population of clear to weakly turbid and cracked euhedral prisms. Most have diameters of about 60  $\mu\text{m}$  and aspect ratios between 2.5 and 4. In CL images, the grains have fine-scale oscillatory zoning and about 20% appear to have rounded cores. Fifty-nine analyses on 59 zircons were undertaken (Figure 3b; Supplementary papers, Table S2.1). Transient instrument instability affected two analyses that are not considered further. Eight analyses have ages younger than the main population and are considered to have suffered Pb-loss that is possibly related to the altered condition of this rock. There are also two analyses with ages that are older than the main population, one is a core with an age of *ca* 590 Ma and the other is an unzoned zircon fragment at *ca* 1105 Ma. The remaining 47 analyses have moderate uranium and Th/U (median 274 ppm and 0.66, respectively) and are all within uncertainty (MSWD = 1.43, POF = 0.03) combining to yield a weighted mean <sup>206</sup>Pb/<sup>238</sup>U age of 472.0  $\pm$  3.6 Ma. This is interpreted as the crystallisation age of this rock. The results of 20 oxygen isotope and 19 hafnium isotope analyses are displayed in Figure 4 and in Supplementary papers, Tables S2.2 and S2.3. Zircon  $\delta^{18}\text{O}$  values range from 7.13 to 8.82‰ and do not form a single population (MSWD = 7.9, POF  $\leq$  0.025). Their robust median is 8.10  $\pm$  0.18/–0.14‰. Nineteen initial  $\epsilon\text{Hf}(t)_{\text{zrn}}$  values from 19 zircons range between –12.8 and –6.3 but are scattered beyond uncertainties (MSWD = 2.8, POF  $\leq$  0.025). A statistically coherent grouping can be made by eliminating the highest and lowest value (MSWD = 1.72, POF = 0.04), which gives a weighted mean  $\epsilon\text{Hf}(t)_{\text{zrn}}$  of –10.46  $\pm$  0.48. This compares with a whole-rock  $\epsilon\text{Nd}(t)$  of –10.0.

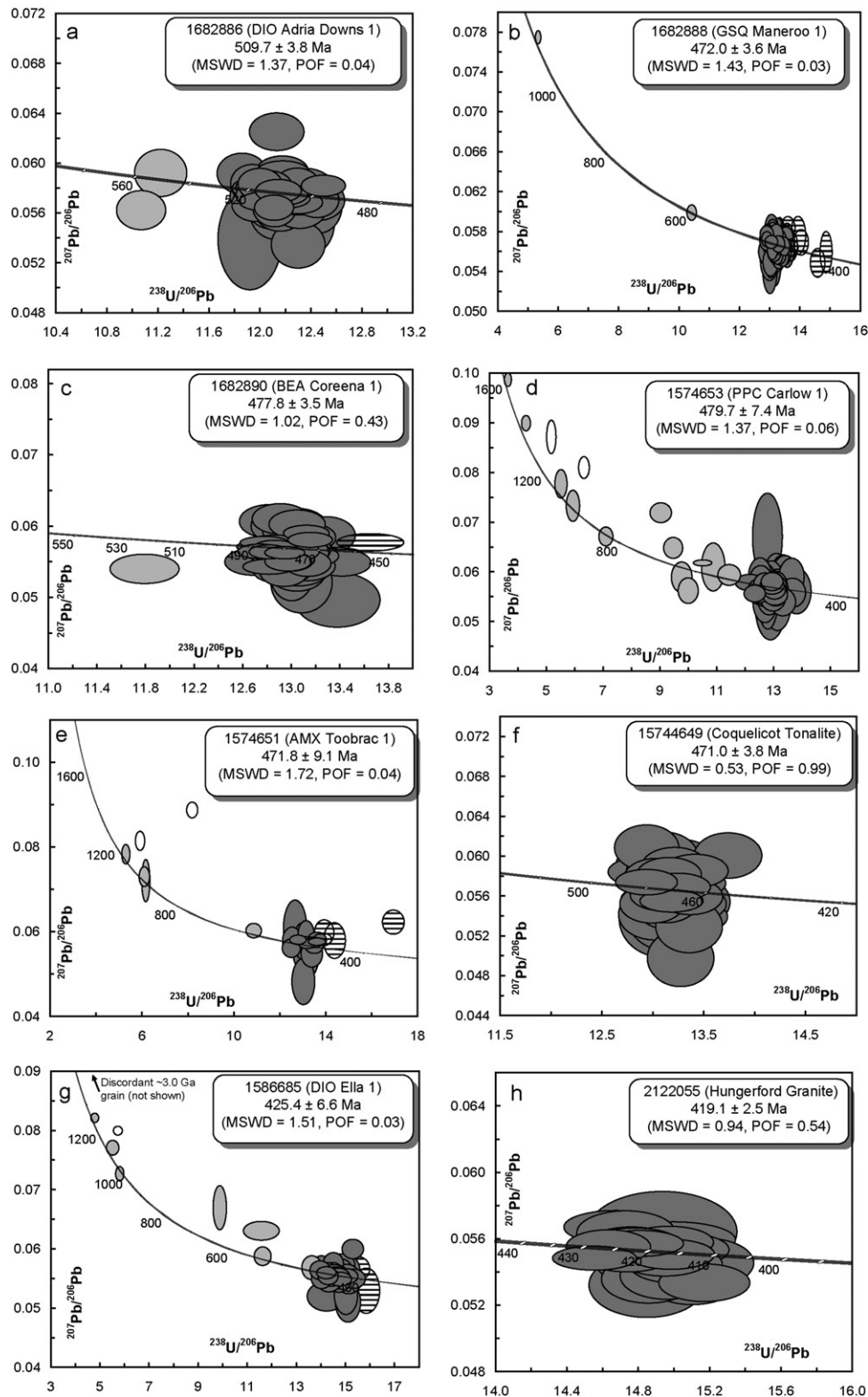
### 1682890 (BEA Coreena 1) – Maneroo volcanics

Sample 1682890 (BEA Coreena 1) is a porphyritic dacite. The sample is one of the least altered of the Ordovician volcanic rocks. It has many similarities to 1682888 (GSQ Maneroo 1) (above), and is an I-type, based on its geochemistry. The zircons recovered are a homogeneous population of clear, euhedral and mostly fragmented grains, many with acicular inclusions. Grain diameters are mostly about 70  $\mu\text{m}$  and aspect ratios for the few intact grains are generally between 2 and 3. Sixty analyses were made on 60 grains from this sample (Figure 3c; Supplementary papers, Table S3.1). An analysis that was affected by instrument instability has been removed from the interpretation. One analysis with an age of *ca* 525 Ma is significantly older than the main population and represents inheritance. A further analysis is significantly younger than the dominant population and is interpreted to have suffered Pb-loss. The remaining 57 analyses have moderate uranium (median 159 ppm) and Th/U (median 0.61) and combine to yield a weighted mean <sup>206</sup>Pb/<sup>238</sup>U age of 477.8  $\pm$  3.5 Ma (MSWD = 1.02, POF = 0.43) for this dacite. Twenty-two oxygen and hafnium isotope analyses were undertaken on zircons from this sample (Figure 4; Supplementary papers, Tables S3.2 and S3.3). Oxygen isotope values ( $\delta^{18}\text{O}_{\text{zrn}}$ ) range between 6.40 and 7.86‰ and do not form a statistically coherent grouping (MSWD = 4.2, POF  $\leq$  0.025). The robust median for all 22 analyses is 7.01  $\pm$  0.12/–0.23‰. Initial  $\epsilon\text{Hf}(t)_{\text{zrn}}$  from 22 analyses range from –8.1 to –3.4 and combines to give a weighted mean value of –6.26  $\pm$  0.29 (MSWD = 0.89, POF = 0.60). The initial whole-rock  $\epsilon\text{Nd}(t)$  is –7.1.

### 1574653 (PPC Carlow 1) – Maneroo volcanics

Sample 1574653 (PPC Carlow 1) is an altered, felsic auto-clastic volcanic. The geochemistry of this sample is





**Figure 3.** (a–m) Tera–Wasserburg concordia plots of SHRIMP U–Pb zircon analyses of igneous rocks from the Thomson Orogen. Dark grey ellipses are analyses used to derive the weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  pooled ages, light grey ellipses are inherited grains, stippled ellipses represent analyses interpreted to have lost radiogenic  $^{206}\text{Pb}$  and unfilled ellipses are pre-1000 Ma and >10% discordant. Poor quality analyses and grains with high common  $^{206}\text{Pb}$  are not plotted. (a) 1682886, DIO Adria Downs 1; (b) 1682888, GSQ Maneroo 1; (c) 1682890, BEA Coreena 1; (d) 1574653, PPC Carlow 1; (e) 1574651, AMX Toobrac 1; (f) 1574649, Coquelicot Tonalite; (g) 1586685, DIO Ella 1; (h) 2122055, Hungerford Granite; (i) 1682891, PPC Carlow 1; (j) 1682892, PPC Gumbardo 1; (k) 1585223, AAE Towerhill 1; (l) 2122056, Currawinya Granite; and (m) 2130082, AOP Scalby 1.



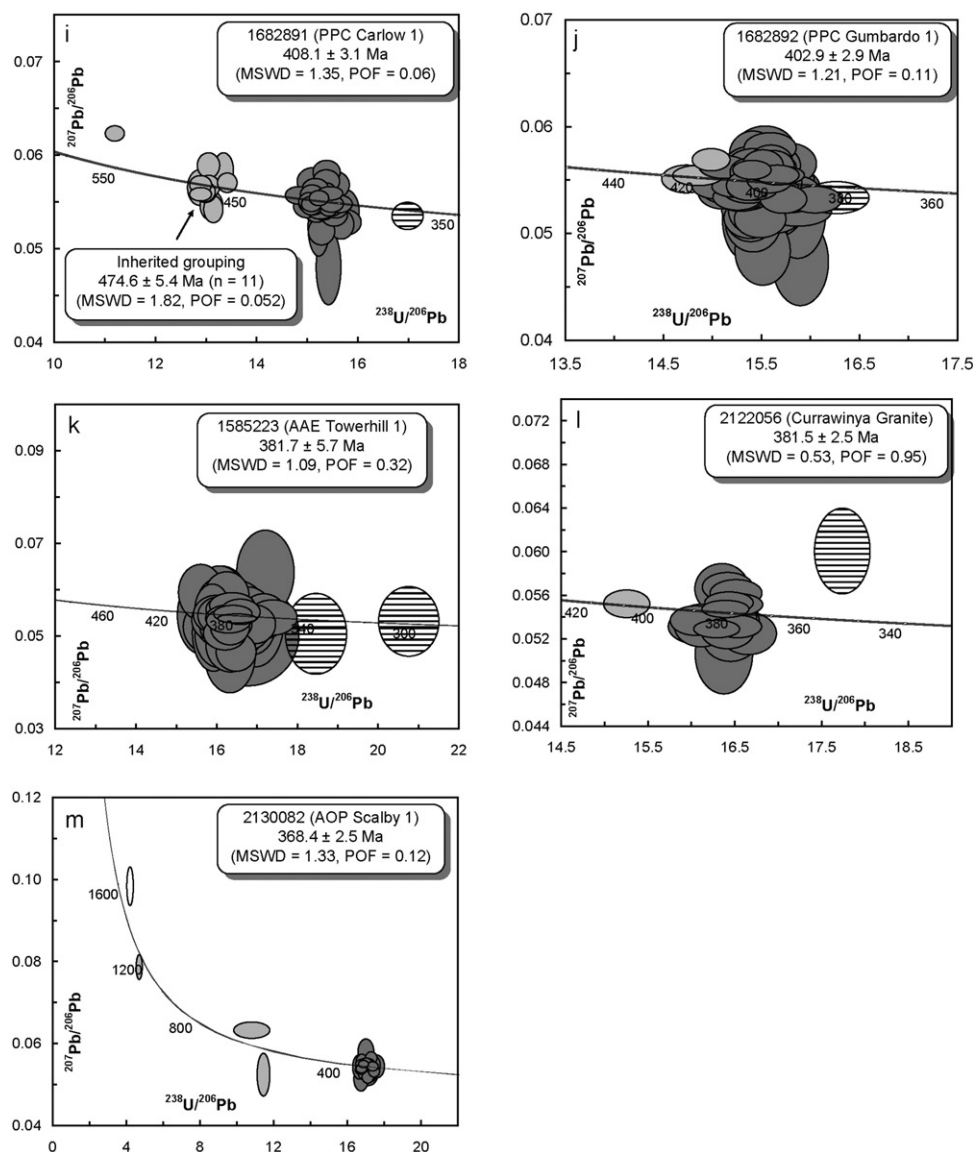
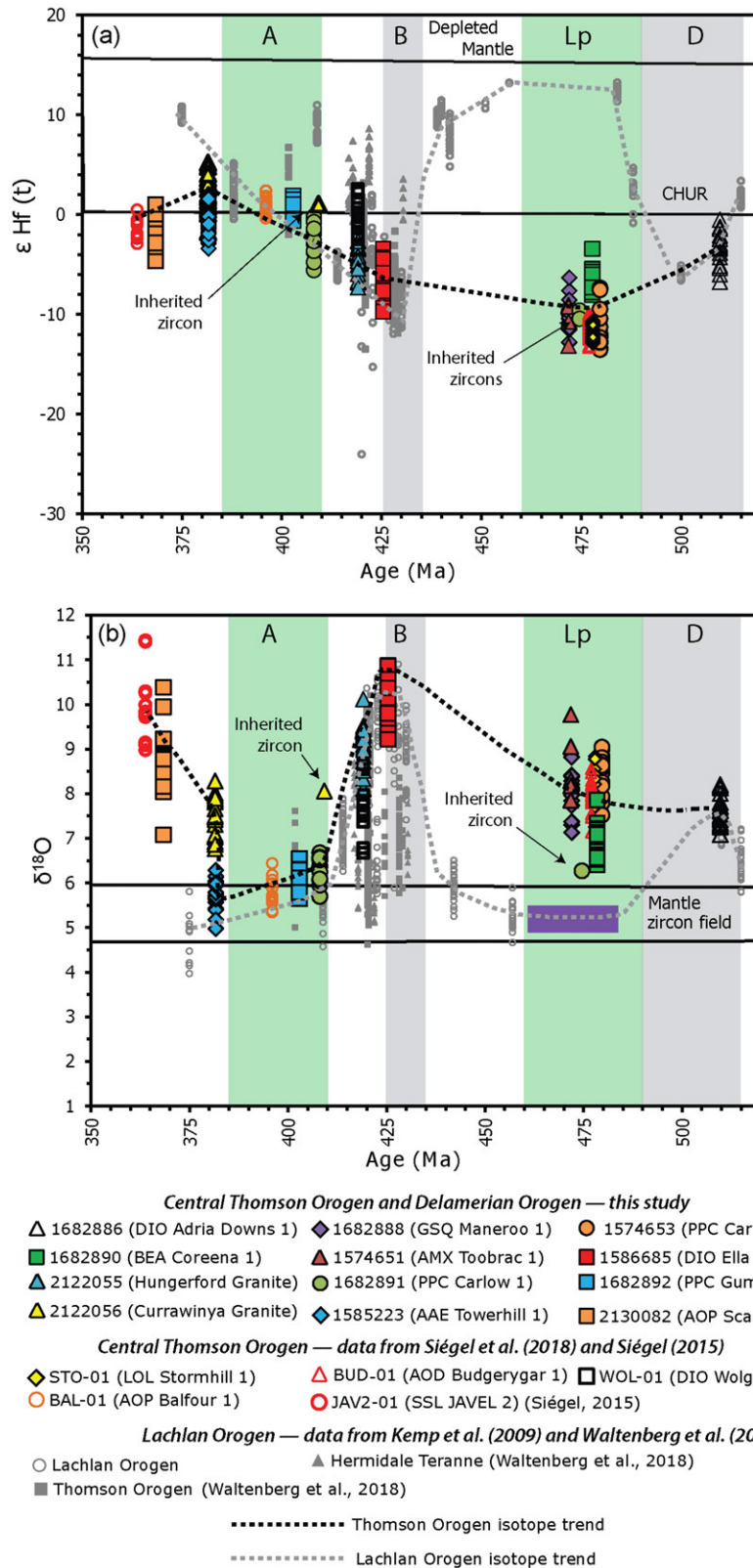


Figure 3. Continued.

equivocal. It is significantly less siliceous than other Ordovician volcanic samples (63 wt%  $\text{SiO}_2$ ). The sample is altered and possibly mineralised (8600 ppm S). The mounted zircons can be separated into two broad types in roughly equal proportions: (1) fragments with crystal faces and more rarely intact grains and (2) rounded (sometimes pitted) and subhedral grains. In CL images, the euhedral population has a moderate luminescence with fine, faint oscillatory growth zoning; the rounded-subrounded grains are variable in their luminescence and internal zoning features. Fifty-three analyses were collected on zircons from this sample. Thirty-nine SHRIMP U–Pb analyses preferentially targeted the euhedral fragments and intact grains. Twelve analyses that are significantly older than the dominant population have a range of ages between *ca* 1603 and *ca* 542 Ma. The majority of these grains have rounded to subhedral morphologies and are interpreted to represent

inheritance. Two further pre-1000 Ma grains are >10% discordant and removed from interpretation. The 39 U–Pb analyses that targeted the more euhedral fragments and intact grains have moderate uranium (median 236 ppm) and Th/U (median 0.66) and combine to give a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $479.7 \pm 7.4$  Ma (MSWD = 1.37, POF = 0.06, Figure 3; Supplementary papers, Table S4.1). Zircon  $\delta^{18}\text{O}$  compositions from 20 analyses range from 7.52 to 9.04‰ and do not form a single population within their uncertainties (MSWD = 9.9, POF < 0.025). They have a combined robust median of  $8.50 + 0.14/-0.33$ ‰. The  $\varepsilon_{\text{Hf}}(t)_{\text{Zrn}}$  values from 18 grains range between –13.5 and –7.4. Three analyses are considered outliers and once removed, result in a grouping of 15 analyses (MSWD = 1.6, POF = 0.074) that give a weighted mean  $\varepsilon_{\text{Hf}}(t)_{\text{Zrn}}$  value of  $-12.18 \pm 0.50$  (Figure 4; Supplementary papers, Tables S4.2 and S4.3). Initial whole-rock  $\varepsilon_{\text{Nd}}(t)$  is –11.3.



**Figure 4.** (a)  $\epsilon_{\text{Hf}}(t)_{\text{Zrn}}$  versus U–Pb age and (b)  $\delta^{18}\text{O}_{\text{Zrn}}$  versus U–Pb age diagrams showing the temporal evolution of magmatism in the central Thomson and Delamerian orogens. Grey shaded time intervals are major orogenic events to have affected the Thomson Orogen and are: D, Delamerian Orogeny (514–490 Ma, Foden *et al.*, 2006); B, Benambran Orogeny (435–425 Ma; Collins, 2002). Green shaded time slices are major extensional events to have affected the Thomson Orogen and are: Lp, Larapinta (490–460 Ma, Fergusson *et al.*, 2007b); and A, Adavale extension (410–385 Ma, Fergusson *et al.*, 2013). Data for the Lachlan Orogen is from Kemp *et al.* (2009) and Waltenberg *et al.* (2018). The purple rectangle in (b) represents the approximate field of unpublished  $\delta^{18}\text{O}_{\text{Zrn}}$  data for Ordovician rocks from the Macquarie Arc (Lachlan Orogen) presented by Kemp and Blevin (2009).

### 1574651 (AMX Toobrac 1)

Sample 1574651 (AMX Toobrac 1) is a biotite–muscovite monzogranite. Although altered, the unit has characteristics (e.g. elevated  $P_2O_5$ , low Zr, LREE, Th/U) that strongly suggest it is S-type (Champion & Bultitude, 2013). Only 52 zircons were separated from this sample and comprise a heterogeneous mix of sizes, shapes, clarity, and colour. Almost all grains are either broken fragments or rounded to subrounded and many are variably cracked. They are clear to partly turbid and colourless to light brown with grain diameters ranging between  $\sim 20$  and  $\sim 100$   $\mu m$ . Luminescence is weak to strong and some grains have a weakly luminescent rim that is visible in reflected light images as zones of likely metamict zircon. Internal zoning patterns are predominantly oscillatory to planar and about half of the grains appear to have rounded cores. Of the 28 U–Pb analyses undertaken, seven were removed from interpretation. One analysis was affected by transient instrument instability, two pre-1000 Ma grains are  $>10\%$  discordant and a further four analyses are significantly younger than the dominant population and are interpreted to have undergone Pb-loss. The overall poor quality of recovered zircons likely contributed to the relatively high proportion of grains interpreted to have suffered Pb-loss. Five analyses are older than the dominant population and have ages of *ca* 2378, *ca* 1154, *ca* 1013, *ca* 985, and *ca* 609 Ma, are interpreted as inheritance. The remaining 16 zircons have moderate uranium concentrations (median 305 ppm) and Th/U ratios (median 0.64) and contribute to a weighted mean  $^{206}Pb/^{238}U$  age of  $471.8 \pm 9.1$  Ma (MSWD = 1.72, POF = 0.04, Figure 3e; Supplementary papers, Table S5.1). This is interpreted as the crystallisation age of this rock. Owing to the scarcity and poor quality of grains recovered from this sample, only seven oxygen and hafnium isotope analyses were undertaken (Figure 4; Supplementary papers, Tables S5.2 and S5.3). Of these, two were carried out on grains interpreted to have undergone Pb-loss and are not considered. The remaining five zircon  $\delta^{18}O$  values range from 7.85 to 9.77‰ but are significantly scattered (MSWD = 32, POF  $\leq 0.025$ ). These analyses have a robust median value of  $8.30 \pm 1.47/-0.44$ ‰. Initial  $\epsilon_{Hf}(t)$  values have a wide range between  $-21.5$  and  $-9.1$  and are significantly dispersed (MSWD = 48). The lowest value appears to be an outlier and after removing it, the remaining four are only slightly dispersed in their  $\epsilon_{Hf}(t)$  (MSWD = 3.19, POF = 0.023) and have a weighted mean  $\epsilon_{Hf}(t)$  value of  $-10.63 \pm 2.72$ . Initial whole-rock  $\epsilon_{Nd}(t)$  is  $-9.1$ .

### 1574649 (Coquelicot Tonalite)

Sample 1574649 (Coquelicot Tonalite) is a foliated biotite–hornblende tonalite. This is the least altered Ordovician sample in this study. It has the lowest silica (59.5 wt%) of the samples in this study and most probably represents a

fractionated mantle melt. The zircons recovered are a homogeneous population of clear, light brown grains with average diameters of about 60  $\mu m$  and aspect ratios between 2 and 2.5. They have a moderate luminescence and are oscillatory zoned. Thirty-seven analyses were made on zircons from this sample. One analysis has anomalous common  $^{206}Pb$  and is removed from interpretation. The remaining 36 analyses have moderate uranium (median 179 ppm) and Th/U (median 0.66) and combine to yield a weighted mean  $^{206}Pb/^{238}U$  age of  $471.0 \pm 3.8$  Ma (MSWD = 0.53, POF = 0.99, Figure 3f; Supplementary papers, Table S6.1). This is interpreted as the crystallisation age of this rock.

### 1586685 (DIO Ella 1) – Ella Granite

Sample 1586685 (DIO Ella 1) is a biotite–muscovite monzogranite. Like the older Toobrac 1 granite, the Ella 1 granite has characteristics, e.g. elevated ASI,  $P_2O_5$ , low Zr, LREE, Th/U, that strongly suggest it is an S-type. The recovered zircons are euhedral, clear to partly turbid and colourless to light brown. Average diameter is  $\sim 40$   $\mu m$  and aspect ratios typically range from 3 to 4 but extend to 8. They have a moderate to strong luminescence, are mostly oscillatory zoned and the majority of grains appear to have rounded cores. Forty-seven analyses were undertaken on 45 zircons (Figure 3g; Supplementary papers, Table S7.1). Two analyses are significantly younger than the dominant population and are interpreted to have lost radiogenic Pb. There are also two pre-1000 Ma grains that are  $>10\%$  discordant and have also been removed from further interpretation. Seven analyses of cores are significantly older than the dominant population and have ages of *ca* 1215, *ca* 1069, *ca* 1020, *ca* 620, *ca* 532 ( $n = 2$ ), and *ca* 456 Ma and are interpreted as inheritance. The dominant zircon population has moderate uranium concentrations (median 495 ppm) and moderate to low Th/U ratios (median 0.16). This grouping comprises 36 analyses that are the same within uncertainty (MSWD = 1.51, POF = 0.03) and combine to yield a  $^{206}Pb/^{238}U$  age of  $425.4 \pm 6.6$  Ma, which is interpreted as the crystallisation age of this rock. Results of 15 oxygen and 16 hafnium isotope analyses are displayed in Figure 4; Supplementary papers, Tables S7.2 and S7.3. The  $\delta^{18}O_{zrn}$  values range from 9.21 to 10.87‰ and are significantly scattered (MSWD = 12.13, POF  $\leq 0.025$ ). Combined, they have a robust median value of  $10.29 \pm 0.09/-0.52$ ‰. Initial  $\epsilon_{Hf}(t)$  from 16 zircons ranges between  $-9.7$  and  $-3.4$  and are also scattered beyond uncertainty (MSWD = 4.42, POF  $\leq 0.025$ ). The scatter is eliminated by removing two analyses (MSWD = 1.52, POF = 0.10) resulting in a combined weighted mean  $\epsilon_{Hf}(t)_{zrn}$  value of  $-6.42 \pm 0.72$ .

### 2122055 (Hungerford Granite)

Sample 2122055 (Hungerford Granite) is a muscovite–biotite monzogranite. The low  $Na_2O$ , high  $K_2O/Na_2O$  and



elevated ASI of this relatively unaltered unit suggest it is an S-type. Zircons recovered are clear and colourless euhedral grains with aspect ratios between 2 and 4 and diameters between  $\sim 40$  and  $\sim 120 \mu\text{m}$ . About 50% are broken fragments. They have a moderate luminescence and display oscillatory to planar zoning. Twenty-three analyses were carried out on 23 zircons from this sample. Uranium concentrations and Th/U ratios are moderate (medians 405 ppm and 0.30, respectively). All 23 zircons analysed have the same radiogenic  $^{206}\text{Pb}/^{238}\text{U}$  within their analytical uncertainties (MSWD = 0.94, POF = 0.54, [Figure 3h](#); [Supplementary papers, Table S8.1](#)) and combine to yield an age of  $419.1 \pm 2.5 \text{ Ma}$ , which is interpreted as the crystallisation age of this rock. Results of 22 oxygen and 19 hafnium zircon analyses are displayed in [Figure 4](#) and [Supplementary papers \(Tables S8.2 and S8.3\)](#). Zircon  $\delta^{18}\text{O}$  values from 22 analyses are dispersed (MSWD = 4.30, POF  $\leq 0.025$ ) and range from 8.11 to 10.12‰. All 22  $\delta^{18}\text{O}_{\text{zrn}}$  values have a robust median of  $9.26 + 0.11/-0.23$ ‰. The 17 initial  $\epsilon\text{Hf}(t)_{\text{zrn}}$  values considered range between  $-7.3$  and  $-2.6$  but are also scattered beyond their individual uncertainties (MSWD = 5.9, POF  $\leq 0.025$ ). They have a robust median value of  $-4.62 + 1.2/-0.80$ .

#### 1682891 (PPC Carlow 1) – Gumbardo Formation

Sample 1682891 (PPC Carlow 1) is a rhyolitic ignimbrite. The geochemical classification of this sample is uncertain. It is slightly less siliceous than other volcanic samples although this in part reflects greater hydration and alteration. Zircons from this rock mostly comprise euhedral grains  $\sim 40 \mu\text{m}$  in diameter and their broken equivalents. Aspect ratios range from 2 to 3 but range up to 5. They have a moderate to bright luminescence with faint oscillatory zoning and rare cores. Fifty-nine analyses were undertaken on 59 grains. One analysis is significantly younger than the dominant population and interpreted to record Pb loss. The 46 analyses from the dominant population have moderate uranium (median 301 ppm) and Th/U ratios (median 0.63) and combine to yield a  $^{206}\text{Pb}/^{238}\text{U}$  age of  $408.1 \pm 3.1 \text{ Ma}$  (MSWD = 1.35, POF = 0.06). This is interpreted to be the eruptive age for this ignimbrite. There is also a single grain at  $\sim 551 \text{ Ma}$  and another population of inherited grains ( $n=11$ ) that have similar morphological and internal zoning patterns as well as uranium and Th/U ratios (medians 207 ppm and 0.61, respectively) to the younger dominant population. These 11 analyses are the same within uncertainty (MSWD = 1.82, POF = 0.05) and combine to give a  $^{206}\text{Pb}/^{238}\text{U}$  age of  $474.6 \pm 5.4 \text{ Ma}$  ([Figure 3i](#); [Supplementary papers, Table S9.1](#)). Hafnium and oxygen isotope analyses were undertaken on 15 zircons from the dominant population ([Figure 4](#); [Supplementary papers, Tables S9.2 and S9.3](#)). The  $\delta^{18}\text{O}_{\text{zrn}}$  values from 14 analyses range from 5.69 to 6.67‰ but are significantly scattered (MSWD = 4.29, POF  $\leq 0.025$ ) and have a robust median value of  $6.30 + 0.24/-0.26$ . An additional analysis of an

inherited grain with an age of  $\sim 466 \text{ Ma}$  has a  $\delta^{18}\text{O}$  value of  $6.27 \pm 0.33$ ‰. Hafnium compositions were determined on 13 zircons from the magmatic population and two zircons from the inherited grouping. Initial  $\epsilon\text{Hf}(t)$  values for the magmatic grouping ranges between  $-5.6$  and  $-0.2$ , and when combined, are heterogeneous (MSWD = 2.10, POF  $\leq 0.025$ ). The heterogeneity can be removed by eliminating the lowest analysis and leaves a weighted mean  $\epsilon\text{Hf}(t)_{\text{zrn}}$  value of  $1.73 \pm 0.82$  (MSWD = 1.70, POF = 0.07). In contrast, the two Hf isotopic values on zircons from the inherited  $\sim 475 \text{ Ma}$  grouping have  $\epsilon\text{Hf}(t)_{\text{zrn}}$  values of  $-9.6$  and  $-10.5$ .

#### 1682892 (PPC Gumbardo 1) – Gumbardo Formation

Sample 1682892 (PPC Gumbardo 1) is a rhyolitic ignimbrite. Geochemistry of this unit is equivocal. Although the ASI suggests it may be an S-type, this may simply reflect some redistribution of CaO and Na<sub>2</sub>O. The mounted zircons are a homogeneous population of euhedral, clear, colourless, and generally equant grains with average diameters of about  $90 \mu\text{m}$ . All grains have fine oscillatory growth zoning. Eighty analyses were undertaken on 80 zircons ([Figure 3j](#); [Supplementary papers, Table S10.1](#)). One analysis is significantly younger than the dominant population and interpreted to have undergone some Pb-loss. There are also three grains at  $\sim 420 \text{ Ma}$  that are significantly older than the dominant population and represent inheritance. The remaining 76 analyses have moderate uranium concentrations and Th/U ratios (medians 182 ppm and 0.86, respectively) and form a single population with a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $402.9 \pm 2.9 \text{ Ma}$  (MSWD = 1.21, POF = 0.11). This is interpreted as the eruptive age of this rock. The results of 19 hafnium and oxygen isotope zircon analyses are displayed in [Figure 4](#) and in [Supplementary papers \(Tables S10.2 and S10.3\)](#). Nineteen  $\delta^{18}\text{O}_{\text{zrn}}$  values range between 5.64 and 6.55‰. Removing the highest analysis leaves a single population (MSWD = 1.67, POF = 0.04) that gives a mean value of  $6.01 \pm 0.15$ ‰. Nineteen initial  $\epsilon\text{Hf}(t)_{\text{zrn}}$  values range from  $-0.6$  to  $+1.9$  and form a single population (MSWD = 1.17, POF = 0.27) with a weighted mean value of  $0.51 \pm 0.32$ .

#### 1585223 (AAE Towerhill 1) – Unnamed unit

Sample 1585223 (AAE Towerhill 1) is a rhyolitic ignimbrite. The elevated Na<sub>2</sub>O and low K<sub>2</sub>O of this sample suggest it is an I-type. Zircons recovered comprise a homogeneous population of euhedral, clear, colourless to light-brown grains, many with acicular inclusions. Average grain diameters are about  $60 \mu\text{m}$  and the majority are broken fragments. The few intact grains have aspect ratios between 2 and 3, but larger broken grains indicate aspect ratios of  $>6$ . They have a moderate luminescence and oscillatory growth zoning. Two analyses are significantly younger than the dominant population and are interpreted to have undergone Pb-loss. The remaining 45 U–Pb zircon analyses

have moderate uranium (median 173 ppm) and Th/U ratios (median 0.71) and have identical radiogenic  $^{206}\text{Pb}/^{238}\text{U}$  within their uncertainties (MSWD = 1.09, POF = 0.32) and yield an age of  $381.7 \pm 5.7$  Ma, which is interpreted as the eruptive age of this rock (Figure 3k; Supplementary papers, Table S11.1). The results of 20 oxygen and 21 hafnium isotope analyses for this sample are shown in Figure 4 and in the Supplementary papers (Tables S11.2 and S11.3). Zircon  $\delta^{18}\text{O}$  values range between 4.97 and 6.28‰ and do not form a single population (MSWD = 6.09, POF  $\leq 0.025$ ). The robust median for all values is  $5.78 + 0.20/-0.14$ ‰. Hafnium isotope values have  $\epsilon\text{Hf}(t)$  values that range from  $-3.4$  to  $+1.6$  but together do not constitute a single population (MSWD = 2.0, POF  $\leq 0.025$ ). Removing two analyses removes the scatter (MSWD = 1.39, POF = 0.13) and gives a weighted mean initial  $\epsilon\text{Hf}(t)_{\text{Zrn}}$  value of  $-1.72 \pm 0.36$ . This unit has a whole-rock  $\epsilon\text{Nd}(t)$  value of  $-3.5$ .

### 2122056 (Currawinya Granite)

Sample 2122056 (Currawinya Granite) is a biotite monzogranite. The Currawinya Granite is geochemically quite similar to the volcanic rock 1585223 (AAE Towerhill 1), although has lower  $\text{Na}_2\text{O}$  and higher  $\text{K}_2\text{O}$ . It is also most likely an I-type. The zircons recovered are clear and colourless euhedral prisms and their broken equivalents. They have a wide range in size from  $\sim 20$  to  $\sim 120$   $\mu\text{m}$  in diameter with aspect ratios from 1 to 9. They have a moderate luminescence and are predominantly oscillatory zoned. Common Pb proportions are generally below 1 wt%; however, the grain with the highest  $^{206}\text{Pb}_c$  (2.8 wt%) also has the lowest  $^{206}\text{Pb}/^{238}\text{U}$  ratio and is therefore been removed from further consideration. One of the remaining 21 analyses is of a distinct core that is significantly older (ca 409 Ma) than the dominant population and is interpreted as inherited. The remaining 20 analyses have moderate uranium concentrations and Th/U ratios (medians 262 ppm and 0.50, respectively). These analyses have the same radiogenic  $^{206}\text{Pb}/^{238}\text{U}$  within their analytical uncertainties (MSWD = 0.53, POF = 0.95) and combine to give an age of  $381.5 \pm 2.5$  Ma, which is interpreted as the crystallisation age of this rock (Figure 3l; Supplementary papers, Table S12.1). Twenty oxygen and 17 hafnium isotope analyses were undertaken on zircons from this sample (Figure 4; Supplementary papers, Tables S12.2 and S12.3). The  $\delta^{18}\text{O}$  values range from 6.76 to 8.28‰ but are dispersed beyond their uncertainties (MSWD = 4.38, POF  $\leq 0.025$ ). Combining all 20  $\delta^{18}\text{O}_{\text{Zrn}}$  values gives a robust median of  $7.45 + 0.36/-0.40$ ‰. Initial  $\epsilon\text{Hf}(t)_{\text{Zrn}}$  values are all positive and spread between 0.1 and 4.8 but are significantly scattered (MSWD = 3.84, POF  $\leq 0.025$ ). They have a robust median  $\epsilon\text{Hf}(t)$  value of  $1.92 + 1.3/-0.97$ . In comparison, the whole-rock initial  $\epsilon\text{Nd}$  is  $-3.42$ .

### 2130082 (AOP Scalby 1) – Scalby Granite

Sample 2130082 (AOP Scalby 1) is a biotite–muscovite granite. The Scalby Granite has characteristics (e.g. elevated ASI,  $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ,  $\text{P}_2\text{O}_5$ , low LREE, Th/U) that indicate that it is an S-type. Zircons recovered are clear and colourless, euhedral, with subordinate subhedral and rounded grains. Grains range from  $\sim 80$  up to  $\sim 300$   $\mu\text{m}$  in length with aspect ratios commonly between 1 and 2 but ranging up to 4. Almost all have some crystal faces and some have pointed prismatic terminations, some of which surround a rounded core. Fewer grains are almost completely rounded and display faint signs of pitting visible in transmitted light. Most grains have a moderate luminescence, although the full range extends from strong to weak, and all grains either display sector or oscillatory zoning. Thirty-four SHRIMP U–Pb analyses were undertaken on 30 zircons from this sample. Of these, one analysis was adversely affected by instrumental instability during data acquisition and is not considered further. Another three with  $^{206}\text{Pb}_c > 1.5$  wt% are also removed from further consideration. A further analysis with a pre-1000 Ma age is  $> 10\%$  discordant and also removed from interpretation. Three analyses of zircon cores are significantly older than the main population and represent inheritance at ca 1240, ca 570, and ca 540 Ma. The remaining 26 analyses have moderate uranium concentrations (median 520 ppm) and low Th/U (median 0.10). All 26 analyses are within uncertainty (MSWD = 1.33, POF = 0.12) and have a  $^{206}\text{Pb}/^{238}\text{U}$  age of  $368.4 \pm 2.5$  Ma, which is interpreted to record the igneous crystallisation age of this rock (Figure 3m; Supplementary papers, Table S13.1). Nineteen oxygen and 17 hafnium isotopic analyses were undertaken on zircons from this sample (Figure 4; Supplementary papers, Tables S13.2 and S13.3).  $\delta^{18}\text{O}_{\text{Zrn}}$  values range from 7.08 to 10.38‰ and are dispersed beyond their uncertainties (MSWD = 9.73, POF  $\leq 0.025$ ). Together they yield a robust median value of  $8.77 + 0.12/-0.30$ ‰. The 17 hafnium isotopic analyses are spread between negative and positive  $\epsilon\text{Hf}(t)$  values ( $-4.7$  to  $1.0$ ) and do not form a single population within uncertainty (MSWD = 6.86, POF  $\leq 0.025$ ). They have a robust median initial  $\epsilon\text{Hf}(t)_{\text{Zrn}}$  value of  $0.01 + 0.46/-2.0$ .

### SHRIMP U–Pb reinterpretation of mounts Z4497 and Z4638

The SHRIMP U–Pb zircon ages for the nine samples mentioned by Draper (2006) and reprocessed with SQUID 2.50 as a part of this work, are all within analytical uncertainty of the original age interpretations. Minor differences between the two sets of age interpretations and their uncertainties are the result of different (1) SHRIMP U–Pb data reduction software, (2) steps used for the propagation of uncertainties related to multiple  $^{206}\text{Pb}/^{238}\text{U}$  calibration sessions, (3) propagation of uncertainties associated with establishing 95% confidence limits, and (4) human

interpretation of complex zircon age patterns. Importantly, the original ages noted by Draper (2006) were processed using the MS Excel-based, SQUID processing package of Ludwig (2001), which in some cases, underestimates uncertainties associated with single spots by factors of between 1.2 and 1.3 (Ludwig, 2009a). Using SQUID 2.50 (Ludwig, 2009b) corrects this issue and establishes better comparability to existing data from the Thomson Orogen (Cross *et al.*, 2015; Cross, Purdy, Bultitude, Brown, & Carr, 2016; Fraser *et al.*, 2014; Kositsin *et al.*, 2015a; Kositsin *et al.*, 2015b; Purdy *et al.*, 2016b).

Where available, whole-rock initial  $\epsilon\text{Nd}$  values correlate very well with zircon  $\epsilon\text{Hf}$  values, as is to be generally expected (Vervoort, Blichert-Toft, Patchett & Albarède, 1999; Vervoort, Plank, & Prytulak, 2011), although agreement is closest using the earlier model of Vervoort, Blichert-Toft, Patchett, and Albarède (1999). In the two samples with most disagreement (1682886 DIO Adria Downs 1 and 2122056 Currawinya Granite), zircon  $\epsilon\text{Hf}(t)$  values are more juvenile than expected, by  $\sim 4$  epsilon units. Interestingly, apart from one sample 2122056 (Currawinya Granite), there is a very good negative linear correlation (correlation coefficient of 0.94) between the available whole-rock  $\epsilon\text{Nd}$  (Ordovician and one Devonian sample) and zircon  $\delta^{18}\text{O}$  values (Table 2). Notably, the units with the most mantle-like oxygen (the Devonian I-type units [1585223 AAE Towerhill 1 and 2122056 Currawinya Granite] with 5.78 and 7.45‰, respectively) still have significantly evolved Nd, with  $\epsilon\text{Nd}$  values of  $-3.5$  to  $-3.4$ , a point we return to below.

There is also a reasonable correlation between  $\delta^{18}\text{O}_{\text{zrn}}$  values and assigned granite types, which given the obvious alteration in many samples, is best viewed as preliminary. I- and A-type igneous rocks range from 5.78 to 8.10‰ (highest values in the Ordovician rocks), in comparison to 8.30 to 10.29‰ for the S-type rocks. There is one exception. The Devonian sample 1682892 (PPC Gumbardo 1), thought to possibly be an S-type, has mantle-like  $\delta^{18}\text{O}$  value (6.01‰) and so the suggested S-type geochemistry may actually reflect alteration. Regardless, the spread in  $\delta^{18}\text{O}$  values, especially for the Ordovician I-type units, suggests involvement of significant supracrustal material in their genesis (as discussed in more detail below).

## Discussion

### Regional correlations

The U–Pb ages for the 13 magmatic samples reported range from the middle Cambrian to the Late Devonian and correlate well with other magmatic events recorded in the Thomson Orogen and adjacent parts of the Delamerian Orogen.

### Cambrian

The oldest sample reported is a rhyolitic ignimbrite with an age of  $509.7 \pm 3.8$  Ma from southwestern Queensland 1682886 (DIO Adria Downs 1). This age is within uncertainty of volcanism recorded in basal volcanics of the Warburton Basin (Mooracoochie Volcanics  $517 \pm 9$  Ma, PIRSA, 2007), along the Cambrian Delamerian margin in the Gnalta Group of western New South Wales (*ca* 510 Ma, see Greenfield *et al.*, 2011) and Mount Stavelly Volcanic Complex of western Victoria (510–500 Ma; Lewis, Taylor, Cayley, Schofield, & Skladzien, 2015; Lewis, Cayley, Duncan, Schofield, & Taylor, 2016).

Carr *et al.* (2014) assigned the rhyolitic ignimbrite from DIO Adria Downs 1 as an extension of the Mooracoochie Volcanics, but the relative isolation of this sample (Figure 1) renders any correlations tenuous. Although components of the Mount Wright Arc in northwest NSW are outlined in geophysical images (Greenfield *et al.*, 2011), little is revealed about the continuation of any such feature into the Warburton Basin area and further into the western Thomson Orogen. The age of the ignimbrite in DIO Adria Downs 1 is consistent with belonging to the Delamerian Orogeny but the interpreted A-type geochemistry suggests an extensional non-arc environment, as suggested by Champion (2016) for this unit and also the Mooracoochie Volcanics. The negative  $\epsilon\text{Hf}(t)_{\text{zrn}}$  and whole-rock  $\epsilon\text{Nd}$  values together with the supracrustal  $\delta^{18}\text{O}_{\text{zrn}}$  values from sample 1682886 (DIO Adria Downs 1) (Table 2) indicate derivation from an evolved supracrustal source. These values are broadly similar to the limited zircon  $\epsilon\text{Hf}(t)$  and  $\delta^{18}\text{O}$  data reported for other Delamerian rocks, presented by Kemp, Hawkesworth, Collins, Gray, and Blevin (2009) and suggest derivation from a similar crustal domain (Figure 4).

### Early Ordovician

Five of the igneous rocks analysed here have Early Ordovician crystallisation ages that range from 480 to 470 Ma. Three volcanic samples from the undercover central Thomson Orogen (1682888 GSQ Maneroo 1, 1682890 BEA Coreena 1 and 1574653 PPC Carlow 1; Table 2) have been assigned by Carr *et al.* (2014) to the informally named Maneroo volcanics and are similar in age and lithology to exposed felsic volcanics in the Charters Towers Province (Seventy Mile Range Group) and Greenvale Province (Balcooma Metavolcanic Group). The Seventy Mile Range Group and Balcooma Metavolcanic Group have SHRIMP U–Pb ages of  $479 \pm 5$  Ma (Perkins, McDougall, & Walshe, 1993) and  $480 \pm 4$  Ma (Rea, 2000; cited in Jell, 2013), respectively, and host significant copper–lead–zinc–gold–silver-bearing volcanic massive sulfide style deposits at the Thalanga, Balcooma and other mines. Importantly, the age obtained for altered felsic volcanic sample 1574653 (PPC Carlow 1) ( $479.7 \pm 7.4$  Ma) confirms the presence of Early Ordovician magmatic Thomson Orogen rocks below the Adavale Basin (Draper, 2006).



The biotite–muscovite granite, sample 1574651 (AMX Toobrac 1) in the undercover central Thomson Orogen and the foliated biotite–hornblende tonalite sample 1574649 (Coquelicot Tonalite) from the outcropping Anakie Province, have ages of  $471.8 \pm 9.1$  and  $471.0 \pm 3.8$  Ma, respectively. These new ages are indistinguishable from SHRIMP U–Pb zircon ages from two other granites intersected in drill holes in the central Thomson Orogen (AOD Budgerygar 1:  $476.9 \pm 3.5$  Ma; LOL Stormhill 1:  $477.9 \pm 2.7$  Ma; Siégl *et al.*, 2018). Crustal involvement is also evident by the five inherited zircons analysed from 1574651 (AMX Toobrac 1), which range from *ca* 2378 to 609 Ma indicating magma interaction with the Thomson beds or similar sedimentary source (Purdy *et al.*, 2016b). This is consistent with the interpreted S-type geochemistry.

The Ordovician extrusive and intrusive I- and S-type rocks documented here and by Siégl *et al.* (2018), extend the known distribution of magmatism in the Thomson Orogen during this time. Similar aged (latest Cambrian to Early Ordovician) I- and S-type intrusive magmatism is also known in the Charters Towers and Lolworth batholiths of the northeastern Thomson Orogen (Fergusson *et al.*, 2013). S-type magmatism is also documented in the Anakie Province, in the same general region as the Coquelicot Tonalite. Early Ordovician I-type tonalites and granites also occur in the Greenvale Province and surrounds (Fergusson *et al.*, 2013). Magmatism during this time was synchronous with deposition of widespread turbiditic deposits (e.g. Warratta Group, Greenfield, Gilmore, & Mills, 2010; Thomson beds, Purdy *et al.*, 2016b).

### Late Silurian

Late Silurian to earliest Devonian (425–419 Ma) aged intrusive rocks are abundant in the southern Thomson Orogen and the Eastern and Central Lachlan Orogen (Armistead & Fraser, 2015; Bodorkos *et al.*, 2013, 2015; Chisholm, Blevin, Downes, & Simpson, 2014; Fraser *et al.*, 2014; Ickert & Williams, 2011; Waltenberg *et al.*, 2018). Samples 1586685 (DIO Ella 1) and 2122055 (Hungerford Granite) analysed here fall into that age category along with the Tibooburra Suite (Greenfield *et al.*, 2010) and intrusive rocks reported by Chisholm *et al.* (2014) and Armistead and Fraser (2015) that are associated with anomalous Au, Mo, W, and base metals at the Cuttaburra and F1 prospects. The biotite–muscovite monzogranite analysed from sample 1586685 (DIO Ella 1) has a crystallisation age of  $425.4 \pm 6.6$  Ma. Recent geophysical interpretation (Purdy *et al.*, 2018) suggests that this intrusion forms part of much larger, batholithic-scale belt of intrusions (Ella belt) in the far southwest of the Thomson Orogen, which also includes leucocratic biotite–muscovite monzogranites intersected in TEA Roseneath 1 ( $419.1 \pm 6.9$  Ma, Siégl *et al.*, 2018) and DIO Wolgolla 1 ( $419.0 \pm 3.1$  Ma, Siégl *et al.*, 2018). Southeast of the Ella belt of intrusions, sample 2122055 (Hungerford Granite), with an age of  $419.1 \pm 2.5$  Ma

(Bultitude & Cross, 2013) is one of the four distinct granites that crop out along the Eulo Ridge basement high.

Both sample 1586685 (DIO Ella 1) and sample 2122055 (Hungerford Granite) have negative  $\epsilon_{\text{Hf(t)}}$  (−6.42 and −4.62, respectively) values coupled with significantly elevated  $\delta^{18}\text{O}_{\text{zrn}}$  (10.29 and 9.26‰, respectively) values consistent with the interpreted S-type nature of these granites. Interestingly, zircon  $\epsilon_{\text{Hf(t)}}$  values are not as evolved as those seen in the Ordovician igneous units, suggesting source components for the Ordovician and Silurian igneous rocks were not the same (Figure 4a).

### Devonian

The Gumbardo Formation is a sequence of volcanic and volcanoclastic rocks that forms the lowermost unit of the entirely subsurface Adavale Basin (see Champion, 2016, figure 1.2), (McKillop, McKellar, Draper, & Hoffman, 2005). The U–Pb geochronology of two rhyolitic ignimbrite samples from the Gumbardo Formation, 1682891 (PPC Carlow 1),  $408.1 \pm 3.1$  Ma and 1682892 (PPC Gumbardo 1),  $402.9 \pm 2.9$  Ma, constrain the lower age and initial phases of basin opening to approximately Pragian (Draper 2006). These ages are within error of other Gumbardo Formation data recently acquired by Asmussen, Bryan, Allen, and Purdy (2018). The inherited zircon population in sample 1682891 (PPC Carlow 1) at *ca* 475 Ma may have been derived from a local volcanic or plutonic source that was mixed with the ignimbrite during eruption or the later phases of magmatic evolution. These inherited grains have  $\epsilon_{\text{Hf(t)}}$  values similar to that of the other Early Ordovician zircons analysed, but an oxygen isotope analysis from only one inherited grain has a  $\delta^{18}\text{O}_{\text{zrn}}$  value of 6.27‰, which is at the lower end for the Early Ordovician grains analysed (Figure 4). In comparison, magmatic grains from this sample have a mantle-like  $\delta^{18}\text{O}_{\text{zrn}}$  value (6.30‰) and a zircon  $\epsilon_{\text{Hf(t)}}$  value (−1.73) that is close to the CHUR line and supports a derivation from a predominantly juvenile magma source (Figure 4). Magmatic zircons in sample 1682892 (PPC Gumbardo 1) have a very similar  $\delta^{18}\text{O}_{\text{zrn}}$  (6.01‰) value and an even more juvenile  $\epsilon_{\text{Hf(t)zrn}}$  (0.51) value. These samples show a distinct shift toward a derivation from more juvenile sources during the late Early Devonian in comparison to the late Silurian to earliest Devonian granitic samples from 1586685 (DIO Ella 1) and 2122055 (Hungerford Granite) where zircon  $\epsilon_{\text{Hf(t)}}$  and  $\delta^{18}\text{O}$  values demonstrate derivation from evolved source magmas (Figure 4).

The rhyolitic ignimbrite, 1585223 (AAE Towerhill 1) lies in the northeast of the undercover Thomson Orogen (Figure 1) and its age of  $381.7 \pm 5.7$  Ma is similar to another nearby, undercover, rhyolitic ignimbrite, which has an SHRIMP U–Pb age of  $392.9 \pm 2.7$  Ma (APC Thunderbolt 1; Kositcin *et al.*, 2015a). These samples lie below the mid Carboniferous to late Middle Triassic Galilee Basin and Mesozoic Eromanga Basin and represent a Devonian felsic volcanic province in this region (Kositcin *et al.*, 2015a).

Outcropping equivalents are sparse but include older components of the Retreat Batholith (e.g. Mount Newsome Granodiorite,  $392.4 \pm 10.2$  Ma, Wood & Lister, 2013), the Theresa Creek Volcanics (reconnaissance maximum depositional age =  $382 \pm 7$  Ma, Cross *et al.*, 2015) and other units assigned to the Ukalunda Shelf (Henderson, Withnall, & Jell, 2013).

Zircons from sample 1585223 (AAE Towerhill 1) have the lowest  $\delta^{18}\text{O}_{\text{zrn}}$  values from the sample suite presented here, marginally negative  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  values and a negative whole-rock initial  $\varepsilon\text{Nd}$  value. Further south, sample 2122056 (Currawinya Granite) (an outcropping unit on the Eulo Ridge basement high) has a similar magmatic age of  $381.5 \pm 2.5$  Ma. This sample has positive  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  values but supracrustal  $\delta^{18}\text{O}_{\text{zrn}}$  values. Intriguingly, it has a negative whole-rock initial  $\varepsilon\text{Nd}$  value of  $-3.42$  that suggests a decoupling between the  $\varepsilon\text{Nd}$  and  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  values for this sample.

The Late Devonian age of  $368.4 \pm 2.5$  Ma for 2130082 (AOP Scalby 1) has a strong temporal relationship with similar granites in the nearby Roma Shelf region that Murray (1994) interpreted to have crystallised between 360 and 355 Ma. Zircons from this sample have  $\varepsilon\text{Hf}(t)$  values that straddle the CHUR line, and supracrustal  $\delta^{18}\text{O}$  values. These features are similar to the results from a nearby basement granite from the Roma Shelf, intersected in SSL Javel 2 and analysed by Siégl (2015) (Figure 4).

### Zircon Hf–O time trends

The zircon U–Pb, Hf, and O isotopes presented here for 13 samples from the Thomson Orogen span from 510 to 368 Ma, and allow for some preliminary interpretations of the apparent, broad isotopic time trends as well as comparison with the adjacent Delamerian and Lachlan orogens.

The negative  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  and whole-rock  $\varepsilon\text{Nd}$  isotope values together with the elevated  $\delta^{18}\text{O}_{\text{zrn}}$  values from sample 1682886 (DIO Adria Downs 1) indicate derivation from an evolved supracrustal source. These values are broadly similar to the limited zircon  $\varepsilon\text{Hf}(t)$  and  $\delta^{18}\text{O}$  values reported for other Delamerian rocks, presented by Kemp *et al.* (2009; Tables 1 and 2) and suggest derivation from a similar crustal domain. In the Delamerian Orogen, Cambrian magmatism is interpreted to be associated with a west-dipping subduction zone that was formerly continuous along the eastern Gondwana margin (Foden *et al.*, 2002). With only one Delamerian-aged sample in our dataset, any correlation between sample 1682886 (DIO Adria Downs 1) with the Delamerian Orogen cannot be properly assessed.

Following the Delamerian Orogeny, a widespread extensional event affected the Tasmanides and extended into central Australia during the late Cambrian and Early Ordovician. Research focused on the outcropping Tasmanides associates this extension with slab roll back and a broadly back-arc setting (Fergusson *et al.*, 2007a, 2007b; Glen, Vaughan, Leat, & Pankhurst, 2005; Henderson,

1986; Stolz, 1995). In the Thomson Orogen and central Australian basins this is known as the Larapinta Event. During this time, protoliths of the vast low-grade metasedimentary rocks, which typify much of the Thomson Orogen, were deposited (Purdy *et al.*, 2016b). Igneous rocks emplaced during this time vary substantially in whole-rock  $\varepsilon\text{Nd}(t)$ ,  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  and  $\delta^{18}\text{O}_{\text{zrn}}$  values between the northern (Thomson Orogen) and southern Tasmanides (as represented by the Macquarie Arc, Lachlan Orogen).

Samples from the Lachlan Orogen emplaced during the Larapinta Event have distinctly juvenile  $\varepsilon\text{Hf}(t)_{\text{zrn}}$ , whole-rock  $\varepsilon\text{Nd}(t)$ , and mantle-like  $\delta^{18}\text{O}_{\text{zrn}}$  values (Figure 4). This is consistent with their spatial location and emplacement within the Macquarie Arc or rift, a series of structural belts comprising volcanic, intrusive, volcanoclastic, and carbonate rocks variably interpreted as an oceanic island arc accreted to the eastern Gondwana margin (Glen *et al.*, 2005; Glen, Walshe, Barron, & Watkins, 1998; Glen, Poudjom Djomani, Korsch, Costelloe, & Dick, 2007) or a zone of localised rifting within an established marginal or back-arc basin (Quinn, Percival, Glen, & Xiao, 2014; Wyborn, 1992).

In stark contrast are four Early Ordovician magmatic samples reported here from the undercover central Thomson Orogen that have evolved  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  and elevated, supracrustal  $\delta^{18}\text{O}$ , as well as negative initial whole-rock  $\varepsilon\text{Nd}(t)$  values, demonstrating derivation from evolved crustal sources (Figure 4; Table 2). Thus, while magmatism in the southern Tasmanides was clearly sourcing juvenile material, magmatism throughout the central Thomson Orogen at this time involved a much greater metasedimentary component. This likely derived from a pre-Thomson beds, sedimentary pile thickened during Delamerian orogenesis that was heated and reworked during Ordovician extension (Collins & Richards, 2008) and suggests that at least part of the Thomson Orogen contains pre-Delamerian material, as suggested by Champion (2016). This postulated older package could be the Machattie beds, which Purdy *et al.* (2016b) suggest represents an extension of the Centralian Superbasin into eastern Australia during the late Neoproterozoic to early Cambrian. Fundamentally, the isotopes confirm significant contrasts in the composition of the deeper crust between the Thomson and Lachlan orogens. This distinction, however, is not universal. More juvenile Ordovician magmatism is also recorded in the northeastern Thomson Orogen, in both the Greenvale (Champion, 2013) and northeastern Charters Towers (Stolz, 1995) regions, interpreted to be arc or back-arc related (Fergusson *et al.*, 2013; Stolz, 1995).

The remaining seven samples reported range from late Silurian to Late Devonian (*ca* 425–368 Ma). The two late Silurian samples (1586685 DIO Ella 1; 2122055 Hungerford Granite) have evolved  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  ( $-6.42$  to  $-4.62$ ) and elevated  $\delta^{18}\text{O}_{\text{zrn}}$  (9.26–10.29‰) that contrasts with the two Middle Devonian samples (1682891 PPC Carlow 1; 1682892 PPC Gumbardo 1), which have markedly higher  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  ( $-1.73$  to  $0.51$ ) values that border the CHUR line and more

mantle-like  $\delta^{18}\text{O}_{\text{zrn}}$  (6.01–6.30‰) values (Figure 4). This apparent trend toward near-juvenile to juvenile  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  is also shown by the Late Devonian samples, 1585223 (AAE Towerhill 1), 2122056 (Currawinya Granite) and 2130082 (AOP Scalby 1), which have  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  values between  $-1.72$  and  $1.92$ . However, except for 1585223 (AAE Towerhill 1), which has distinctly mantle-like  $\delta^{18}\text{O}_{\text{zrn}}$  (5.78‰) value, 2122056 (Currawinya Granite) and 2130082 (AOP Scalby 1) have supracrustal  $\delta^{18}\text{O}_{\text{zrn}}$  (7.45–8.77‰) values. This uncommon isotopic signature of juvenile to near-juvenile  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  but supracrustal  $\delta^{18}\text{O}_{\text{zrn}}$  values may be explained by the reworking of juvenile sediments sourced from nearby, Early Devonian juvenile magmatism, a phenomenon that has previously been reported for S-type granites in the New England Orogen (Kemp *et al.*, 2009; Jeon, Williams, & Bennett, 2014).

Overall, our  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  data for the Thomson Orogen from the late Silurian to Late Devonian show a gradual increase from distinctly evolved in the late Silurian to juvenile and near-juvenile from the late Early Devonian to Late Devonian (Figure 4a). A trend, together with supporting  $\varepsilon\text{Nd}(t)_{\text{wr}}$  and  $\delta^{18}\text{O}_{\text{zrn}}$  data was also noted for Lachlan Orogen samples presented by Kemp *et al.* (2009) (Figure 4). These researchers suggested that periods of dominantly evolved  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  and whole-rock  $\varepsilon\text{Nd}(t)$  as well as supracrustal  $\delta^{18}\text{O}_{\text{zrn}}$  indicate contractional orogenic episodes where higher relative proportions of metasedimentary material are incorporated into magmas. Conversely, periods of dominantly juvenile  $\varepsilon\text{Hf}(t)_{\text{zrn}}$ , whole-rock  $\varepsilon\text{Nd}(t)$  and mantle-like  $\delta^{18}\text{O}_{\text{zrn}}$  indicate increased mantle input during extensional episodes.

The Tasmanides experienced a major deformation event (Benambran Orogeny) between *ca* 435 and 425 Ma (Collins, 2002) that is commonly associated with subduction lock up (Fergusson, 2003; Glen *et al.*, 2005; Glen, Djomani, Korsch, Costelloe, & Dick, 2007; Gray & Foster, 2004; Henderson *et al.*, 2011; VandenBerg *et al.*, 2000; Vos, Bierlein, & Philips, 2007). The evolved zircon  $\varepsilon\text{Hf}(t)$  and supracrustal  $\delta^{18}\text{O}$  values reported for samples, 1586685 (DIO Ella 1) and 2122055 (Hungerford Granite) accord with the majority of the available zircon  $\varepsilon\text{Hf}(t)$  and  $\delta^{18}\text{O}$  isotopic data from magmatic rocks emplaced during or immediately following the Benambran Orogeny (430–420 Ma) from the Thomson and Lachlan orogens (Figure 4). The apparent zircon Hf–O isotopic similarity of late Silurian magmatic rocks across the Thomson and Lachlan orogens demonstrates the broad isotopic-time signature of the Benambran Orogeny.

An extensional event that resulted in opening of the Adavale Basin and emplacement of the Gumbardo Formation (samples, 1682891 PPC Carlow 1 and 1682892 PPC Gumbardo 1) affected the Thomson Orogen in the Early Devonian. Rhyolitic ignimbrite emplaced at this time (1682892 PPC Gumbardo 1) has the most juvenile compositions of this age in the Thomson Orogen ( $\varepsilon\text{Hf}(t)_{\text{zrn}}$  value of  $0.51$  and mantle-like  $\delta^{18}\text{O}$  value of  $6.01\text{‰}$ ) highlighting the importance of this extensional event that resulted in a very

widespread array of Devonian basins (*e.g.* Barrolka Trough, Warrabin Trough, Adavale Basin). This apparent trend of increasing  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  and decreasing  $\delta^{18}\text{O}_{\text{zrn}}$  values of Early Devonian rocks relative to broadly Benambran-aged magmatism (430–420 Ma), was also observed in Lachlan Orogen samples reported by Kemp *et al.* (2009) (Figure 4).

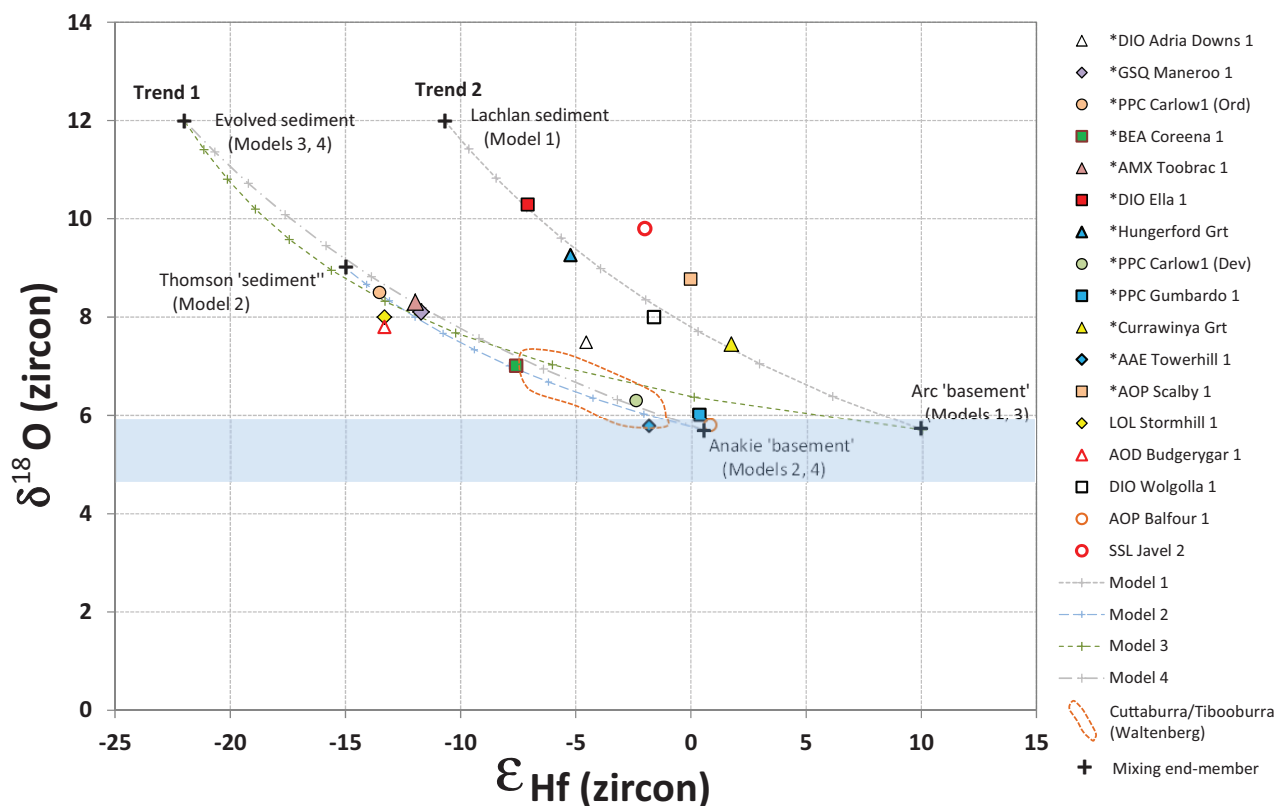
The Hf–O isotopic signature of the Late Devonian samples appears to deviate from the observed trend seen in the Early Devonian samples (Figure 4). Although all samples have juvenile to near-juvenile  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  values, 158223 (Towerhill 1), located in the central-northern Thomson Orogen is distinctive by mantle-like  $\delta^{18}\text{O}_{\text{zrn}}$  values whereas three samples in the south of the orogen, are characterised by supracrustal  $\delta^{18}\text{O}_{\text{zrn}}$  values (Figure 4). This could suggest that in the southern Thomson Orogen, Late Devonian magmatism was characterised by rapid crustal recycling of juvenile material possibly related to the 390–380 Ma Tabberabberan Orogeny.

### Thomson and Lachlan orogens – Hf–O and Nd–O isotopic trends

The new Hf–O isotopic data fall into two subgroups lying along two discrete mixing trends in Hf–O space (Figure 5). These subgroups still hold when Hf isotopic signatures are adjusted to the one age *ca* 370 Ma (*i.e.* older units corrected for radiogenic growth of  $^{176}\text{Hf}/^{177}\text{Hf}$ , assuming a  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of  $0.015$ ; *e.g.* Griffin *et al.*, 2002; Figure 5; Supplementary papers, Figure S15). The one exception to this is 1682886 (DIO Adria Downs 1); it is noted that in this sample, the zircon Hf signature appears to be decoupled from the whole-rock Nd signature (as the sample lies on the Nd–O trend; Supplementary papers, Figure S16). A variety of possible, simple, mixing models are displayed on Figure 5 and for Nd–O in Supplementary papers, Figure S16. Although somewhat simplistic, this modelling does illustrate a number of points: (1) one subgroup appears to have incorporated a significantly more evolved (*i.e.* more negative  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  and  $\varepsilon\text{Nd}_{\text{wr}}$ ), most likely supracrustal, component (Trend 1), (2) the other subgroup can be successfully modelled using an average Lachlan Orogen sediment (average from Kemp *et al.*, 2008) (Trend 2), and (3) juvenile endmembers are more equivocal and may represent mantle-derived material or, for the more isotopically evolved metasediment trend, possibly pre-existing basement such as that exemplified by the Coquelicot Tonalite.

It is noteworthy that granite samples from the Thomson Orogen analysed by Siégl *et al.* (2018) also fall along the same two trends on Figure 5. The relevance of the two trends, and the applicability of the Lachlan Orogen sediment end-member (Trend 2), becomes more apparent when the geographic locations of the samples (Figure 6) are considered. The samples that form Trend 2 (the possible mixing trend with Lachlan-like sediment) all occur in the southern third of the Thomson Orogen and are geographically adjacent to the Lachlan Orogen. These are



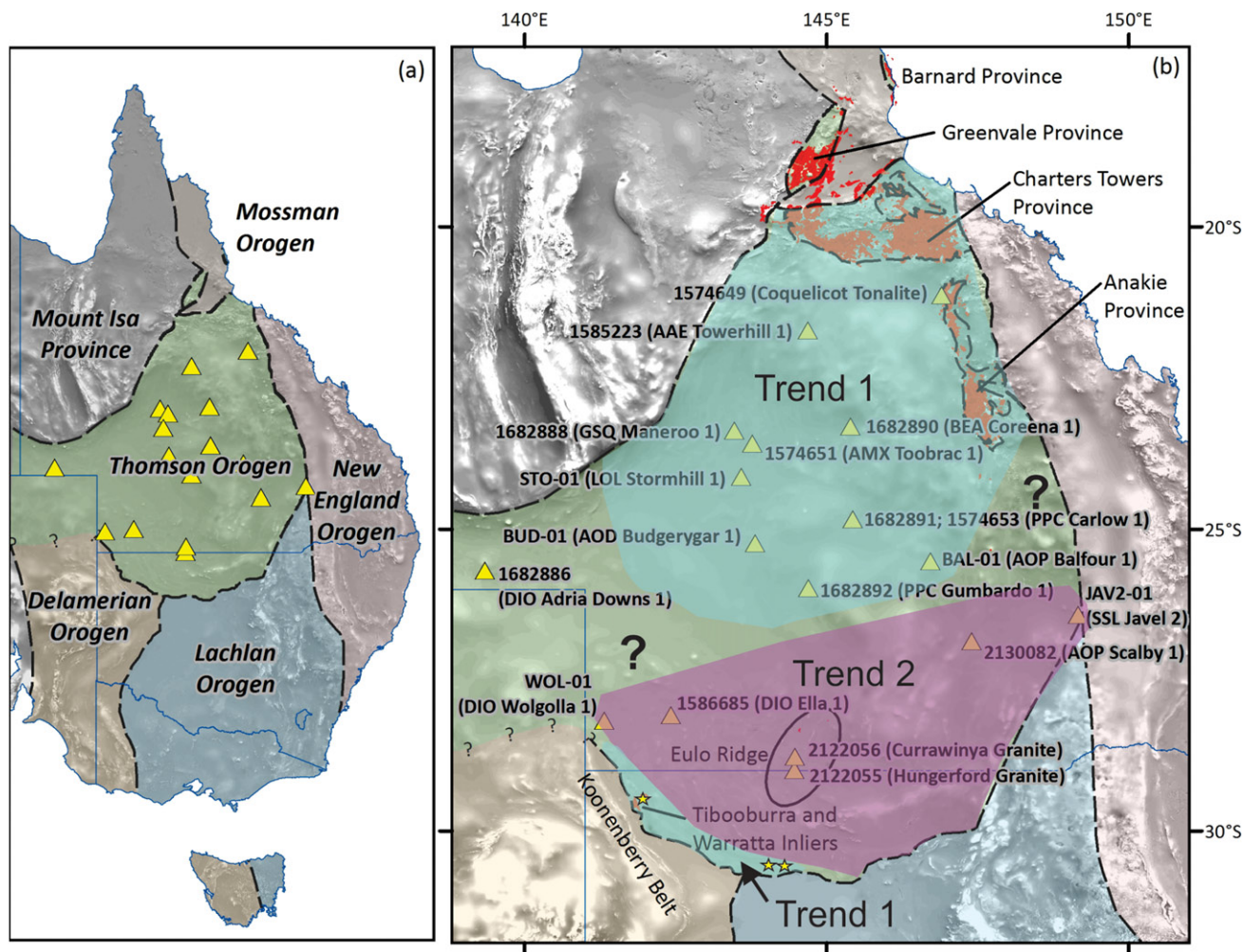


**Figure 5.** Hf–O (zircon) isotopic variation for igneous rocks of the Thomson Orogen. Hf isotopic signatures (Table 2) have been time corrected to 370 Ma (*i.e.* units corrected for radiogenic growth of  $^{176}\text{Hf}/^{177}\text{Hf}$ , assuming a  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of 0.015, *e.g.* Griffin *et al.*, 2002; uncorrected and corrected Hf isotope values are shown in Supplementary papers (Figure S15). Model end-members are as follows: Model 1: mix of juvenile arc endmember ( $\epsilon\text{Hf}$  of 10.0,  $\delta^{18}\text{O}_{\text{zrn}} = 5.7$ ) and metasediment equivalent to Lachlan Fold Belt metasediment ( $\epsilon\text{Hf} = -10.7$ ,  $\delta^{18}\text{O}_{\text{zrn}} = 12$ , from Kemp *et al.*, 2008). Model 2: mix of Anakie Inlier tonalitic basement ( $\epsilon\text{Hf} = 0.5$  and  $\delta^{18}\text{O}_{\text{zrn}} = 5.7$ ) and metasediment equivalent to most evolved S-type granite ( $\epsilon\text{Hf} = -15$ ,  $\delta^{18}\text{O}_{\text{zrn}} = 9$ ). Model 3: mix of juvenile arc ( $\epsilon\text{Hf} = 10.0$  and  $\delta^{18}\text{O}_{\text{zrn}} = 5.7$ ) and hypothetical evolved metasediment ( $\epsilon\text{Hf} = -22$ ,  $\delta^{18}\text{O}_{\text{zrn}} = 12$ ). Model 4: mix of mix of Anakie Inlier tonalitic basement ( $\epsilon\text{Hf} = 0.5$  and  $\delta^{18}\text{O}_{\text{zrn}} = 5.7$ ) and hypothetical evolved metasediment ( $\epsilon\text{Hf} = -22$ ,  $\delta^{18}\text{O}_{\text{zrn}} = 12$ ). Pluses correspond to 10% mixing increments.

geographically separate from the Trend 1 samples with the modelled more evolved Hf sediment end-member, which fall into a domain concentrated in the northern two-thirds of the Thomson Orogen. Recent Hf–O data from magmatic rocks from the southwestern part of the Thomson Orogen (Waltenberg *et al.*, 2018) also fall along the more evolved, Trend 1 (Figure 5). The latter samples (Tibooburra and Cuttaburra) are geographically separate from the samples analysed here. They occur close to the southwest margin of the Thomson Orogen (Figure 6) and correspond to the Warratta Group domain of Waltenberg *et al.* (2018). It is not clear if this domain is geographically isolated from the main Trend 1 domain to the north.

The trends and the mixing models suggest that the felsic igneous rocks of the Thomson Orogen probably interacted with two spatially- and isotopically-distinct metasedimentary protoliths (which may or may not represent rocks of similar age). The interpretation of the two mixing trends and their spatial distinction is equivocal. On the basis of the isotopic data alone it is difficult to discriminate between models that suggest the two metasedimentary end-members represent distinct protoliths (*e.g.* different age and/or different crustal

blocks) or simply just reflect a provenance change within the one general sequence. We contend that the best constraints for the interpretation of the Trend 1 sediments in the northern half of the Thomson Orogen come from their spatial association with the *ca* 480–470 Ma igneous magmatism. The presence of Early Ordovician S-type magmatism in this region is considered unlikely unless the sedimentary protolith had been through a prior crustal thickening event, similar to that advocated for magmatism in the Lachlan Orogen to the south (Collins & Richards, 2008). This is particularly the case if tectonic models that advocate an oceanic crust basement for (parts of) the Thomson Orogen (Glen *et al.*, 2013) are correct. In this scenario, metasediments in the northern Thomson Orogen underwent thickening during the slightly earlier Delamerian Orogen (*ca* 514–490 Ma; *e.g.* Glen, 2013; Foden, Elburg, Dougherty-Page, & Burt, 2006). These metasediments underwent subsequent partial melting in the Early Ordovician, probably as a result of the widespread extension interpreted at this time in the northern Thomson Orogen (Fergusson *et al.*, 2007b). Our preferred model, therefore, suggests that the northern half of the Thomson Orogen, at least, is underlain by



**Figure 6.** Spatial distribution of the more evolved (in green) versus less evolved (in pink) metasedimentary end-members, as deduced from simple modelling of the Hf–O isotopic signatures of igneous rocks from basement drill core and outcrop (Figure 5). Distribution superimposed on the locations of drill holes in the Thomson Orogen.

Delamerian or older metasedimentary crust (*i.e.* corresponding to the location of Trend 1 metasediments). Additional support for this comes from the similar Hf–O mixing trend evident in the southwest Thomson Orogen (data of Waltenberg *et al.*, 2018; Figure 6). In this latter region it is clear that Delamerian and older crust, which outcrops in the nearby Koonenberry region (Greenfield *et al.*, 2010), underlies that part of the Thomson Orogen.

In this model, the absence of Early Ordovician magmatism (extrusive or intrusive) within the Trend 2 isotopic domain is interpreted to indicate that the latter metasediments form part of a younger, post-Delamerian sequence. Given the similarity with Lachlan Orogen metasediments (which can be successfully modelled as the Trend 2 metasediment end-member; Figure 6) we speculate that these metasediments form an extension of the Ordovician metasediments of the Lachlan Orogen. Of course, the Trend 2 metasediments may indeed be older, *i.e.* pre-Delamerian Orogeny. Ireland, Flöttmann, Fanning, Gibson, and Preiss (1998), for example, show that a provenance switch from local-derived (Australian craton) detritus to the Gondwana-

provenance typical of the Lachlan Orogen metasediments is recorded in the early Cambrian Adelaidean metasediments in southeastern South Australia, prior to the Delamerian Orogeny. A similar scenario is also feasible for the Trend 1 and 2 domains in the Thomson Orogen, such that the Trend 2 domain represents the influx of the Gondwana detritus into a slightly younger sequence of the same pre-Delamerian metasedimentary package. Although further work is required to discriminate between the different possible scenarios for the Trend 2 metasediments, we suggest that the spatial distribution of Trend 1 metasediments, particularly where associated with Early Ordovician magmatism, can be taken as the minimum distribution of pre-Delamerian Orogeny basement in the Thomson Orogen.

The association of the Trend 1 sediments in the northern half of the Thomson Orogen, and the occurrence of the Ordovician *ca* 480–470 Ma igneous magmatism may suggest that the northern part of the orogen forms a distinct, older basement terrane relative to the southern part, which may be more akin to the Lachlan Orogen

(Champion, 2016). One key to further constrain, or otherwise, this possibility would be by a better definition of the respective isotopically juvenile end-members for the two mixing trends. Unfortunately, the isotopic data are equivocal. The modelling is permissive of either mantle-derived material or crustal reworking of such material. This is especially the case for Trend 2. Trend 1, however, is just as explicable as reworking of older basement material, as for example, possibly represented by the Coquelicot Tonalite (although no Hf or Nd data are available for this unit). In the above discussion, we have inferred that the distinct evolved protoliths identified in the Hf–O and Nd–O models are most likely metasedimentary in origin. This is largely based on both the S-type nature of the more evolved granites and their elevated  $^{18}\text{O}$  signatures. We cannot, however, unequivocally rule out that these identified protoliths may be wholly or partly infracrustal in nature, that is, represent nonsedimentary basement. Assuming the latter is correct only reinforces our conclusions regarding the possible different basement blocks in the northern and southern Thomson Orogen.

## Conclusions

Zircon U–Pb ages and Hf–O isotopes as well as whole-rock geochemistry and Sm–Nd isotopic results presented here provide important constraints for the development of the Thomson Orogen as well as reveal fundamental differences and similarities with the Lachlan Orogen through time.

The new U–Pb ages for the undercover parts of the Thomson Orogen closely match rocks in the outcropping regions of the orogen. Five of the igneous rocks analysed have Early Ordovician crystallisation ages that range from 480 to 470 Ma and comprise both S- and I-type granites. Volcanic and intrusive rocks outcrop in the Charters Towers, Greenvale, and Anakie provinces have similar ages. Magmatism throughout the Thomson Orogen during this time is interpreted to have occurred in an overall extensional tectonic regime during the Larapinta Event (Fergusson *et al.*, 2007b). Two granitic samples, 1586685 (DIO Ella 1) and 2122055 (Hungerford Granite) have latest Silurian to earliest Devonian ages of  $425.4 \pm 6.6$  and  $419.1 \pm 2.5$  Ma, respectively, and are a part of a batholithic-scale belt of intrusions termed the Ella belt (Purdy *et al.*, 2018). Magmatism of this age is related to the Benambran Orogeny (435–425 Ma; Collins, 2002) and occurs in the southern Thomson, Charters Towers Province, and Lachlan orogens. Following this period of compression, the Thomson Orogen returned to an extensional regime as shown by Gumbardo Formation ignimbrites in samples 1682891 (PPC Carlow 1) and 1682892 (PPC Gumbardo 1), which lie at the base of the Adavale Basin and have ages of  $408.1 \pm 3.1$  and  $402.9 \pm 2.9$  Ma, respectively. These ages are similar to granites of the Amarra Suite of the Lolworth Batholith in the Charters Towers Province. Rhyolitic ignimbrite from sample 1585223 (AAE Towerhill 1) in the

northern Thomson Orogen has a Middle Devonian age of  $381.7 \pm 5.7$  Ma. This is identical within uncertainty of sample 2122056 (Currawinya Granite;  $381.5 \pm 2.5$  Ma) in the southern part of the orogen as well as outcropping granites of the Retreat Batholith in the Anakie Inlier. The youngest sample investigated, 2310082 (AOP Scalby 1;  $368.4 \pm 2.5$  Ma) is an S-type granite in the southeastern Thomson Orogen and is probably associated with tectonics related with the New England Orogen to the east. The oldest sample investigated and the most westerly (1682886 DIO Adria Downs;  $509.7 \pm 3.8$  Ma), is probably not related to the Thomson Orogen but is potentially a component of the Delamerian Orogen.

Hafnium, Nd, and O isotopes for the Early Ordovician samples from the central, undercover Thomson Orogen are in stark contrast to similarly aged rocks in the Lachlan Orogen. These Thomson Orogen samples have distinctly evolved  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  and  $\varepsilon\text{Nd}_{\text{wr}}$  values as well as elevated  $\delta^{18}\text{O}_{\text{zrn}}$  values, suggesting significant interaction with a supracrustal component, whereas similar aged rocks from the Macquarie Arc in the Lachlan Fold Belt reported by Kemp *et al.* (2009), have distinctly juvenile  $\varepsilon\text{Hf}(t)_{\text{zrn}}$ , whole-rock  $\varepsilon\text{Nd}$  and mantle-like  $\delta^{18}\text{O}_{\text{zrn}}$  values (Figure 4; Table 2). These contrasting isotopic characteristics suggest a major difference in the composition of the deep crust between these two orogens. This is further supported by modelling of the available Thomson Orogen Hf–O isotopic data that suggests that the felsic igneous rocks from the central and northern Thomson Orogen incorporated more evolved metasedimentary sources than those in the southern third of the Thomson Orogen (Figure 5). The spatial association of the more evolved sediments and the *ca* 480–470 Ma igneous magmatism provides further constraints. The requirement from the Early Ordovician felsic magmatism for prior crustal thickening (to allow subsequent melts) suggests that the more evolved metasedimentary end-member represents a stratigraphically lower, that is, older pre-Delamerian package. Therefore, we speculate that the northern part of the Thomson Orogen may form a distinct, older basement terrane relative to the southern part, which may be more akin to the Lachlan Orogen.

The Hf–O isotope time-signature of the late Silurian to Late Devonian samples can be linked with the evolution of the Thomson Orogen. Significant crustal reworking associated with the Benambran Orogeny (435–425 Ma) is evident in the two late Silurian samples (1586685 DIO Ella 1; 2122055 Hungerford Granite) that have evolved  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  (–6.42 to –4.62) and supracrustal  $\delta^{18}\text{O}_{\text{zrn}}$  (9.26–10.29‰) values. These values contrast with the Early Devonian samples (1682891 PPC Carlow 1; 1682892 PPC Gumbardo 1) that have distinctly higher  $\varepsilon\text{Hf}(t)_{\text{zrn}}$  (–1.73 to 0.51) and more mantle-like  $\delta^{18}\text{O}_{\text{zrn}}$  (6.01–6.30‰) values that likely reflects an increased mantle input during an extensional episode related to the development of the Adavale Basin. Intriguingly, two Late Devonian samples from the southern Thomson Orogen (2122056 Currawinya Granite,



2130082 AOP Scalby 1) have juvenile  $\varepsilon\text{Hf}(t)_{\text{Zrn}}$  (0.01–1.92) but supracrustal  $\delta^{18}\text{O}_{\text{Zrn}}$  (7.45–8.77‰) values. This uncommon Hf–O isotope signature may reflect rapid recycling of juvenile material related to contraction during the Tabberabberan Orogeny.

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## Disclosure Statement

No potential conflict of interest was reported by the authors.

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